AA12 – Investigating the Processability of Low Grade Bauxite Available in Jamaica

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Abstract

Jamalco's bauxite reserves have deteriorated in quality mainly due to a decrease in the available alumina, and an increase in the reactive silica, boehmite, goethite and phosphorus content. This has resulted in decreased alumina recovery, and increased production costs resulting from increased caustic loss, increased scaling on heat exchange surfaces, and decreased efficiencies. Low temperature alumina refineries, such as Jamalco, must determine their ability to process deteriorating bauxite quality to remain viable. This paper explores the results of extensive laboratory experiments investigating the processability of some of the lowest grade bauxite available in Jamaica and its impact on bauxite residue settling and chemical additive consumption. The impact of variability in reactive silica, aluminous goethite and boehmite content is explored.

Keywords: Bauxite residue, Reactive silica, Aluminous goethite, Boehmite, Hydroxamated flocculants (HX)

1. Introduction

Jamalco is a low temperature alumina refinery in Clarendon, Jamaica processing Jamaican bauxite. Good quality bauxite, sometimes referred to as Jamaica-1 bauxite (boehmite < 3 % and < 30 % of the iron mineral as goethite), has been mostly depleted [1]. Remaining bauxite stores consist of higher boehmite and goethite content, coupled with increased reactive silica and corresponding decreased available alumina content. These types of bauxites present many processing challenges and refineries must explore adaptations to the processing of these more difficult bauxites. The practical approach would be to blend the lower grade bauxites with the Jamaica-1 bauxite to maintain a consistent bauxite feed, however this investigation presents a case study in processing the worst-case type of bauxite blends.

This experiment investigated three major parameters characterizing some of the poorest grade bauxite available: % reactive silica, % aluminous goethite and % boehmite content. Four blends of increasing concentrations were created for each. Albeit the aim was to keep the remaining parameters constant, variation was experienced, especially in the available alumina and phosphate content, which impacted the results. For the purposes of this paper, available alumina will refer to alumina species that are soluble below 150 °C. The % goethite refers to the mass ratio of goethite content compared to the measurable iron content of the bauxite, and similarly the % aluminous goethite refers to the ratio of aluminous goethite compared to the iron content of the bauxite. The chemical composition of the bauxite blends used is shown in Table 1 below.

2. Experimental Method

Each custom bauxite blend was digested with clean spent liquor (CSL), the amount of bauxite calculated to achieve 0.735 blow-off A/C ratio, and the amount of lime needed for phosphorous control (79 – 97 % Calcia). The slurry was digested in a Parr reactor in the laboratory for 35 minutes at 150 °C. The digested slurry was split into eight 1000 mL cylinders and thickener overflow liquor at about 96 °C was added as dilution, up to the 1 L mark to target a solids content of 60 kg/m^3 in each measuring cylinder. A solids test was done on a sample of the blow off slurry to calculate the volume of slurry needed (average 0.35 L) and the volume of dilution liquor needed (average 0.65 L) to achieve the 60 kg/m^3 target. The diluted slurry was reheated to average 92 °C and settling tests performed using 0.1 % solution of modified hydroxamate flocculant. Settling rates were measured by timing the fall of the interface between the 0.9 L and 0.7 L cylinder marks. Supernatant clarity was measured with a Turbidimeter in NTU. Residue compaction was assessed by measuring the height of solids in the base of the cylinder after waiting 30 minutes and was expressed in L. A solids test was done on two of the eight cylinders after completion to determine the average solids content.

Table 1. Chemical composition of bauxite blends used.

Experimental Blends	Total Al_2O_3 (%)	Available Al_2O_3 (%)	Boehmite (%)	SiO_2 (%)	$RSiO_2$ (%)	Fe_2O_3 (%)	P_2O_5 (%)	TiO_2 (%)	Goethite Ratio ($\frac{G}{H+G}$)	Al. Goethite Ratio ($\frac{Al\,G}{H+G}$)
Reactive Silica Blend 1	48.7	42.0	0.48	3.6	2.2	19.0	0.22	2.6	0.40	0.32
Reactive Silica Blend 2	46.4	37.6	0.73	6.0	4.4	18.1	0.39	2.3	0.40	0.32
Reactive Silica Blend 3	44.1	34.7	1.97	9.2	6.6	17.4	0.32	2.2	0.48	0.38
Reactive Silica Blend 4	42.3	19.9	2.22	12.4	7.1	17.3	0.25	2.2	0.48	0.39
Aluminous Goethite Blend 1	48.6	43.1	0.34	2.2	1.3	20.6	0.17	2.6	0.35	0.28
Aluminous Goethite Blend 2	48.6	42.2	0.71	3.3	2.1	18.8	0.82	2.7	0.48	0.38
Aluminous Goethite Blend 3	47.0	39.5	0.80	2.9	1.9	18.1	1.94	2.7	0.66	0.53
Aluminous Goethite Blend 4	46.3	37.9	0.99	1.8	1.2	18.5	3.10	2.7	0.79	0.64
Boehmite Blend 1	48.2	42.1	0.96	2.9	2.6	17.4	0.18	2.5	0.34	0.27
Boehmite Blend 2	48.1	39.9	2.25	4.0	3.8	17.9	0.21	2.4	0.38	0.30
Boehmite Blend 3	48.1	38.5	3.95	4.5	4.2	17.4	0.19	2.4	0.36	0.29
Boehmite Blend 4	48.3	36.7	5.57	5.0	4.3	16.7	0.16	2.4	0.36	0.29

3. Summary of Findings

3.1 Reactive Silica

Increases in the % reactive silica has been known to impact bauxite processability in the following ways: increased formation of Desilication Product (DSP) through reaction with caustic soda, increased scaling on heat exchange surfaces, decreased settling rates, decreased overflow clarity, decreased mud compaction, and increased required flocculant dosages. The increased formation of DSP increases the mud load, and additionally, most of the liquor silica content also recrystallizes out of the circuit with the red mud also increasing the mud load.

The increase in the mud load observed in the investigations are shown in Table 2 below. As the % reactive silica increased, the blow-off solids, which was used as a measure of the mud load generated, also increased. The increase was as high as four times the normal mud load for the high reactive silica blend (7 %) and dilution up to 85 % was needed to achieve the target solids in the thickener simulation. It is worth mentioning that the sharp decrease in % available alumina in the blends also contributed to the increase in the mud load generated.

Table 2. Table showing slurry solids for % reactive silica experiments.

Reactive Silica (%)	**Available Al_2O_3 (%)**	**P_2O_5 (%)**	**Blow Off Ratio**		**Blow Off Solids (kg/m^3)**		**Cylinder Solids (kg/m^3)**		**Dilution %**	**Average Temperature (°C)**
			Target	**Actual**	**Target**	**Actual**	**Target**	**Actual**		
2.19	42.02	0.22	0.735	0.730	70-80	78.4	60	73.7	48	93
4.39	37.55	0.39	0.735	0.698	70-80	85.9	60	73.4	48	93
6.57	34.71	0.32	0.735	0.690	70-80	137.4	60	75.6	58	90
7.06	19.88	0.25	0.735	0.689	70-80	301.5	60	60.6	85	94

As flocculant dosages increased, the settling rate increased which can be seen in Figure 1 below. As the % reactive silica increased, the settling rate also increased, however the settling rate was unimpacted by changes in the % available alumina.

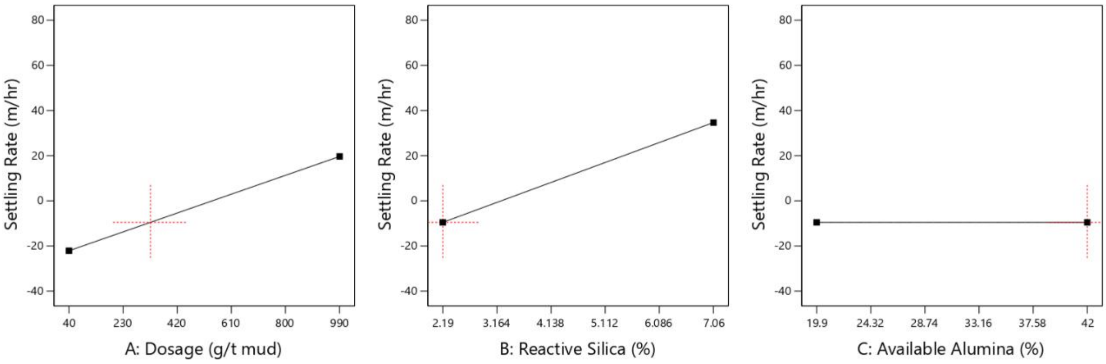

Figure 1. Charts showing settling rate against flocculant dosage (left), % reactive silica (middle) and % available alumina (right).

As flocculant dosages increased, the liquor clarity improved, with NTU values decreasing from 1800 to approximately 100. The clarity also improved with increases in % reactive silica, while the clarity was not impacted by changes in the % available alumina. This is shown in Figure 2 below.

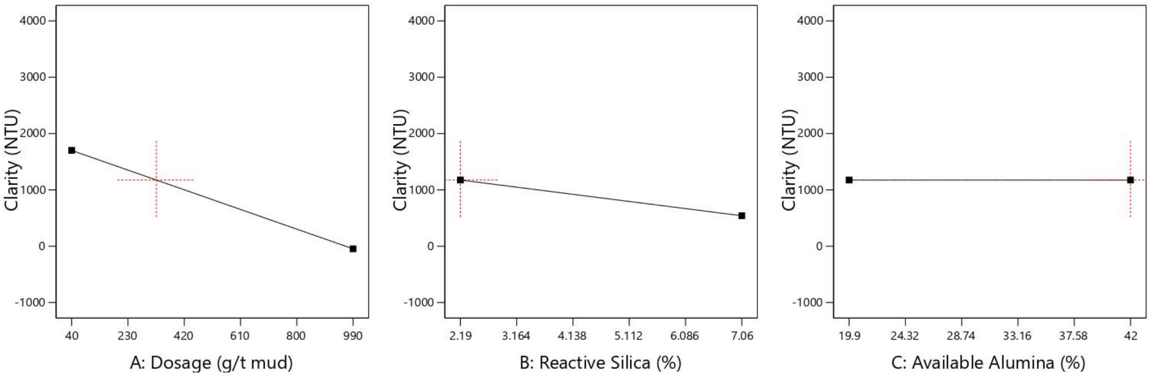

Figure 2. Charts showing clarity against flocculant dosage (left), % reactive silica (middle) and % available alumina (right).

The compaction improved with increased flocculant dosages shown by the settled bed height decreasing from 0.47 L to 0.29 L. The compaction also improved with increasing % reactive silica, but the changes in % available alumina did not impact compaction. These are shown in Figure 3 below. The increase flocculant consumption was also impacted by the decrease in the available alumina, which increases the mud load. However, higher flocculant dosages are required to settle high DSP mud residue, as the solids concentration and mud load increases. This is because the changes in the solid's concentration impacts the particle size, and the aggregate structure impacts the flocculation response of the mud residue [2].

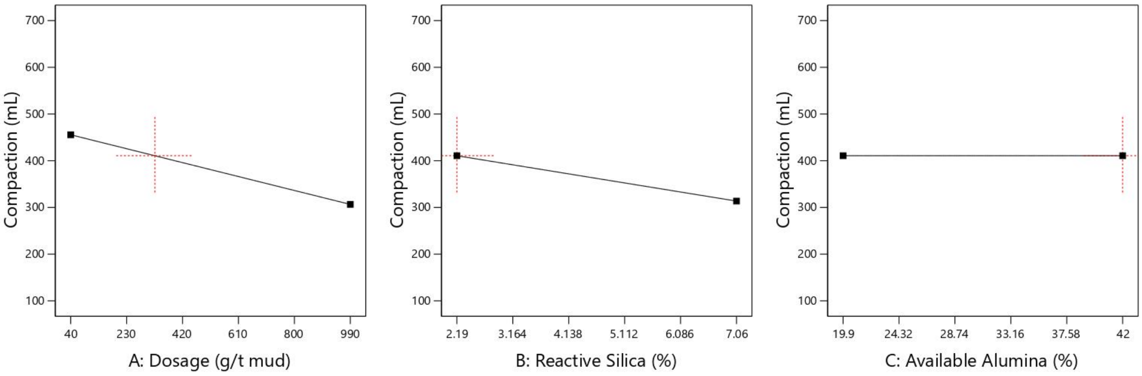

Figure 3. Charts showing compaction against flocculant dosage (left), % reactive silica (middle) and % available alumina (right).

DSP impacts mud settling behavior by decreasing the effective surface area of mud slurry available for flocculant activity. Higher reactive silica bauxite produces finer DSP particles (< 1 µm). The research points to two lines of thought; the first being DSP precipitating onto the surface of the mud particles, thereby changing the surface properties and making less surface available for flocculant adsorption, and thus influencing aggregation kinetics and aggregate density [2]. The other school of thought is that DSP precipitates as a distinct minor phase which increases the number of particles in the slurry, and aggregation is impacted by the activity of the new surfaces [2].

The increase in reactive silica, with higher DSP content, hinders flocculation, with the flocculant efficacy becoming heavily dependent on the active flocculant functionalities and their potential to interact with the surfaces. Research has shown hydroxamate flocculants outperforms the polyacrylate flocculants in handling high DSP mud [2]. For Jamalco, to process high reactive silica bauxite, the mud residue will need to be moved out of the washing train quicker than its typical bauxite residue to prevent the build-up of mud levels in the vessels. The fast-settling DSP particles coupled with an increased mud volume, cause the mud levels to increase rapidly. To effectively process this type of bauxite, higher flocculant dosages, high-rate vessels that will accommodate larger volumes, as well as utilizing eductor feed technology which facilitates greater dilution of the feed stream would be needed.

3.2 Aluminous Goethite

Iron-bearing minerals (mostly hematite and goethite) are the major constituents of bauxite residue and have the potential to be one of the greatest impactors of residue behavior. Goethite has inferior dewaterability compared to hematite because of its shape and fine particle size. The needle-like structure of goethite reduces the surface area of the mud particles available for flocculant activity (like the behavior of DSP particles) [3]. For flocculant activity to be effective, the slurry solids must be sufficiently low. Aluminous goethite has a plate-like structure which produces aggregate structures with a low degree of freedom (Df), the number of directions in which a particle can move freely. With less range of motion, for effective flocculation, a lower solids concentration is required [3]. This also has implications for the maximum compaction possible upon settling and the viscosity of the mud.

The results obtained in the investigations for each of the aluminous goethite blends tested are shown in Table 3 below. As the % aluminous goethite increased, the blow-off solids and mud load also increased. The increase was as high as three times the normal mud load for the 0.64 % aluminous goethite blend. Of note is that the stepwise decrease in % available alumina also contributed to the increase in the mud load generated, like the case of the % reactive silica tests, however the extent of the decrease and the consequent impact was less. The increase in the goethite content also saw a corresponding increase in the phosphorus content simultaneously.

The mud load increased to 3 times the normal, and the amount of dilution needed to achieve target solids was significantly increased to 78 % dilution. There was a significant increase in the Phosphorus content of the bauxite blends which required more lime for phosphate control, and hence making a large impact on the mud load results.

Table 3. Table showing slurry solids for % Aluminous Goethite experiments.

Aluminous Goethite (%)	**Available Alumina (%)**	**Reactive Silica (%)**	**P_2O_5 (%)**	**Blow Off Ratio**		**Blow Off Solids**		**Cylinder Solids**		**Dilution (%)**	**Average Temperature (°C)**
				Target	**Actual**	**Target**	**Actual**	**Target**	**Actual**		
0.28	43.09	1.3	0.17	0.735	0.730	70-80	67	60	52.4	58	91
0.38	42.15	2.1	0.82	0.735	0.723	70-80	94	60	49.1	62	92
0.53	39.49	1.9	1.94	0.735	0.692	70-80	134	60	60.1	67	92
0.64	37.89	1.2	3.10	0.735	0.677	70-80	209.9	60	85.9	78	92

The settling rates were seen to increase from 6 to 48 m/h with increasing flocculant dosages. The settling rate, however, remained at an average of 28 m/h as the % aluminous goethite and as the % available alumina decreased as shown in figure 4 below.

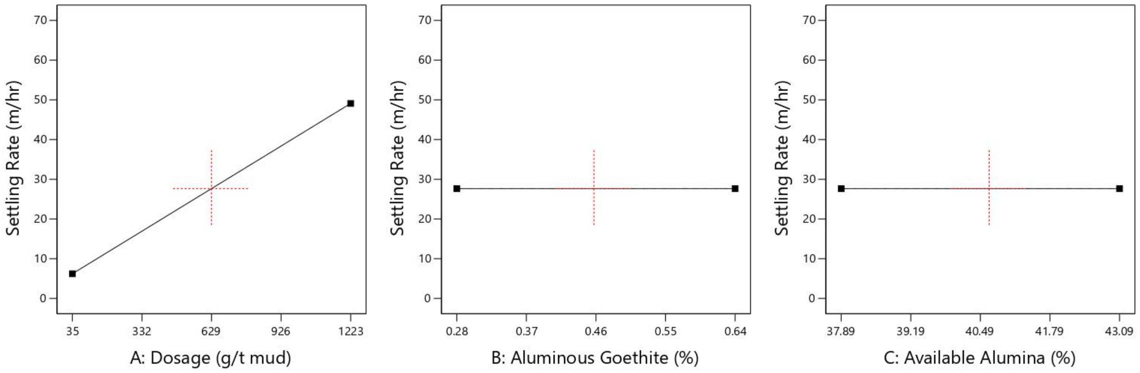

Figure 4. Charts showing settling rate against flocculant dosage (left), % aluminous goethite (middle) and % available alumina (right).

As the flocculant dosage is increased the liquor clarity improved with the NTU decreasing from 1000 to 141 NTU. The clarity was not impacted by increases in the % aluminous goethite or by the % available alumina increasing as shown in figure 5 below.

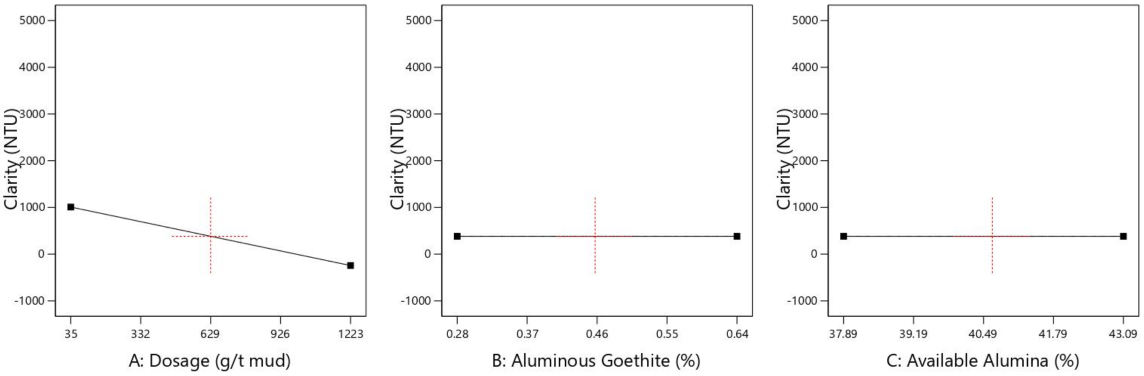

Figure 5. Charts showing clarity against flocculant dosage (left), % aluminous goethite (middle) and % available alumina (right).

As the flocculant dosage is increased, the compaction improved with the mud bed volume decreasing from 0.38 to 0.24 L. The compaction was not impacted by increasing the % aluminous goethite or % available alumina as shown in figure 6 below.

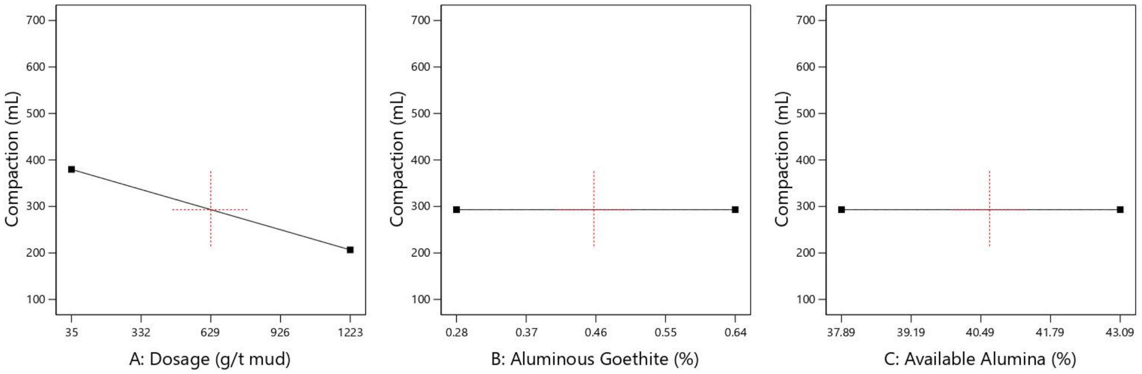

Figure 6. Charts showing clarity against flocculant dosage (left), % aluminous goethite (middle) and % available alumina (right).

The compaction for the % aluminous goethite blends were the poorest of all the tests done because of the rheology impacts of the aluminous goethite sediments. The A/C ratios achieved were also the lowest of all the tests. As the flocculant dosage increased, the settling rate increased, and the liquor clarity improved, then stabilized at about 120g/ton. There was no significant improvement observed in compaction with flocculant dosage increases.

A suspension of finer particles will display a higher effective volume fraction from surface chemistry effects and will lead to an increased viscosity [3]. When bauxite residue samples with similar viscosities of 500 mPa are compared, the goethite-rich Jamaican bauxite samples were found to have much lower solids concentrations (380 g/L) compared with other samples (650 g/L). This has implications for the pumpability of high goethite mud residue. In combination with the greatly increased surface area, higher particle numbers will hinder flocculation and set-up requirements for high flocculant dosages and solids dilution prior to flocculation [3]. The experimental data supports this as the highest bed height seen throughout all the data for the three process parameters was seen in the Aluminous goethite (660 mL after 30 minutes).

Red mud is highly thixotropic with rheological properties that strongly depend on its chemical composition and flocculant dosages, and the research shows that for some muds the yield stress typically ranges from 5–60 Pa [8]. Furthermore, below the stipulated range, the mud begins to act like a solid and beyond the upper limit the mud acts like a viscous fluid [8]. High goethitic content in mud is known to contribute to this type of behavior.

Aluminous goethite rich bauxites present several processing challenges under low temperature digestion conditions. The particle size of goethite is smaller than that of hematite thus resulting in an increase in the specific surface area of bauxite and by extension, the mud generated [1]. With the increase in the specific surface area of bauxite and mud, the viscosity of the associated goethite rich mud slurry increases as well, despite the decrease in solids concentration. This increase is mainly attributed to the lower density associated with aluminous goethite versus that of hematite. It is also to be noted that the compaction of bauxite residue reduces with an increase in goethite in bauxite [1]. The 2015 North Manchester (NM) trial executed at Jamalco indicates that the NM bauxite is a goethite rich bauxite that is high in phosphorus content. The research reveals that boehmite reversion has a strong correlation with both goethitic alumina as well as phosphorus [4].

Aluminous goethite appears to be an effective seed for alumina reversion [5] as well as apatite [4]. It impacts on the mud circuit by reducing compaction in settler mud beds, increasing viscosity of discharged mud, and increasing alumina reversion due to the seeding effect of aluminous goethite. Due to its seeding effect under mud washing conditions, goethite is a significant cause of alumina losses [6]. High molecular weight polyacrylates can settle residues with high aluminous goethite content at even faster rates, however with poor overflow clarities. Flocculant co-dosing (a combination of polyacrylate hydroxamate flocculants) gives the best attributes of both types of flocculants [1] with the modified hydroxamate flocculant utilized in these tests having the impact of the combination of polyacrylate and hydroxamate flocculants, with only one flocculant being used.

The very fine goethite particles in mud residue limit the underflow densities able to be achieved. The research has shown that there is a linear relationship between the specific surface area of bauxite residue and its goethite content, and the same unit mass of bauxite residue will contain more particles if the goethite content is higher [3]. The flocculation and handling of a suspension is significantly impacted by a higher number of particles within the same unit mass of solids. This explains why the solids content of the blow-off slurry increased to twice and three times the typical solids content, respectively, as the % aluminous goethite increases to 0.53 % and 0.64 %.

The addition of a rheology or viscosity modifier would help to reduce the viscosity of the settled mud of a raked thickener, decrease the torque necessary to move the rake blade through the mud, as well as increase the achievable underflow rate [9]. A viscosity modifier is recommended since it may also increase the solids content, greater solids density at a given rake load, increased pumping capacity, minimized gel strength for re-establishing shear stress condition such as during an emergency equipment shutdown, and life expansion of residue disposal areas by increasing mud de-liquoring capabilities [9], [10].

3.3 Boehmite

Boehmite and gibbsite are the two main alumina containing compounds in bauxite deposits. Boehmite content is usually found towards the surface of bauxite deposits in seasonal tropical regions. This distribution of boehmite and gibbsite is attributed to high surface temperatures and dry conditions during the dry season allowing gibbsite to dehydrate to boehmite, and thermodynamic conditions where boehmite is the crystallizing phase rather than gibbsite [7]. This may imply that the composition of bauxite pits can change with extremities of weather conditions over time.

Boehmite is not dissolved under low temperature digestion conditions and so represents alumina that is unavailable for low digestion temperature plants such as Jamalco. Boehmite has only half the solubility of gibbsite in caustic solutions under comparable digestion conditions. At 135 °C, Gibbsite is soluble to 0.67 A/C ratio, but boehmite is only soluble to 0.33 A/C at 160 g/l caustic concentrations. Boehmite requires 249 °C for a 0.67 A/C ratio at the same caustic concentration.

The results obtained in the investigations for each of the four boehmite blends tested are shown in Table 4 below. As the % boehmite increased, the blow-off solids generated (mud load) also increased. The increase was as high as twice the normal mud load for the 5.57 % boehmite blend. Additionally, the stepwise decrease in % available alumina contributed to the increase in the mud load generated like the case of the % reactive silica tests, however the change and consequent impact was less. As the % boehmite increased, the mud load increased to twice the typical levels, and the amount of dilution needed to achieve target solids saw a corresponding increase.

Table 4. Table showing slurry solids for % Boehmite experiments.

Boehmite (%)	**Available Alumina (%)**	**Reactive Silica (%)**	**P_2O_5 (%)**	**Blow Off Ratio**		**Blow Off Solids**		**Cylinder Solids**		**Dilution %**	**Average Temperature (°C)**
				Target	**Actual**	**Target**	**Actual**	**Target**	**Actual**		
0.96	42.1	2.58	0.18	0.735	0.718	70-80	69	60	32.9	70	92
2.25	39.9	3.77	0.21	0.735	0.729	70-80	75	60	50.1	68	94
3.95	38.5	4.15	0.19	0.735	0.707	70-80	201	60	61	65	94
5.57	36.7	4.31	0.16	0.735	0.702	70-80	136	60	57.2	62	91

As the flocculant dosage increased, the settling rate decreased. The settling rate was not impacted by the increasing % boehmite or % available alumina as shown in figure 7 below.

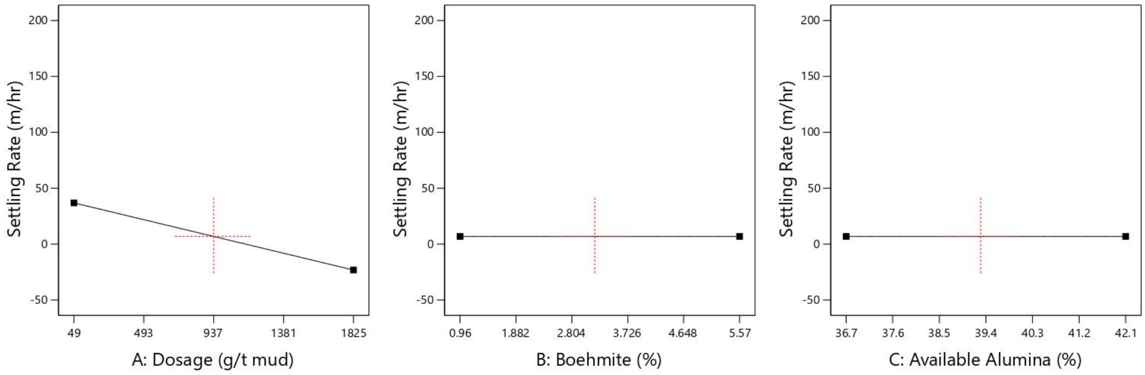

Figure 7. Charts showing settling rate against flocculant dosage (left), % boehmite (middle) and % available alumina (right).

As the flocculant dosage is increased, the liquor clarity improved with the NTU decreasing from 1000 to 121 NTU. The clarity was not impacted by the increasing % aluminous goethite or by the % available alumina as shown in figure 8 below.

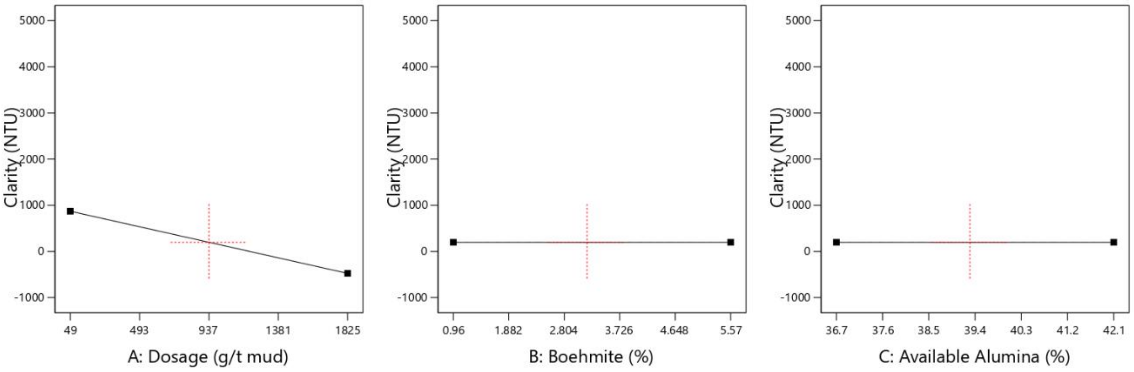

Figure 8. Charts showing clarity against flocculant dosage (left), % boehmite (middle) and % available alumina (right).

The compaction improved with increasing flocculant dosages, with the mud bed volume decreasing from 0.24 to 0.17 L. The compaction, however, remained unaffected as the % boehmite and % gibbsite decreased as shown in figure 9 below.

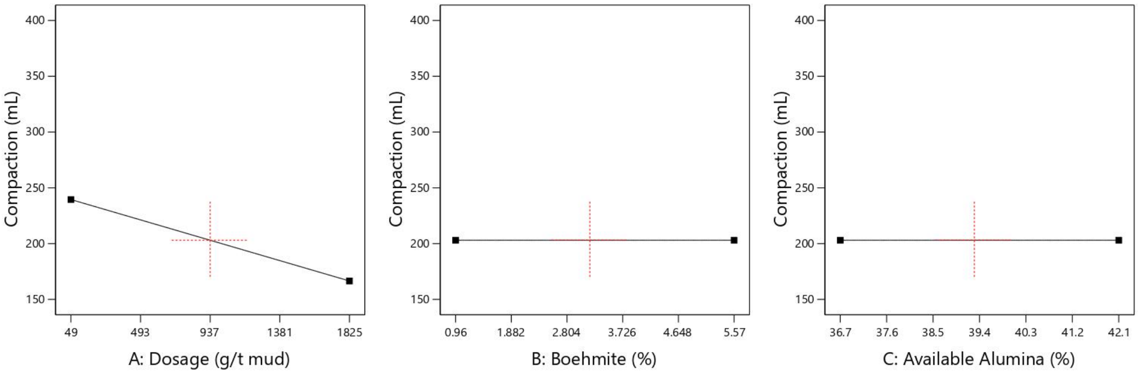

Figure 9. Charts showing compaction against flocculant dosage (left), % boehmite (middle) and % available alumina (right).

After digestion, the presence of boehmite promotes the precipitation of dissolved alumina. It acts as a seed to precipitate gibbsite alumina from solution to form additional boehmite. This is known as “boehmite reversion” which causes increasing mud loads in the mud circuit and increased recovery losses. Boehmite reversion also impacts flocculation effectiveness due to a higher solid’s concentration in the feed well. In addition to increased mud loads and recovery losses, undigested boehmite causes changes in mud settling behavior due to the bauxite mineralogy and bauxite blending (a stable bauxite blend is required for optimal operation).

Higher settling rates were seen in the experimental data at lower flocculant dosages, especially for the higher boehmite concentrated blends. This is most likely because of an increased mud load with higher velocities causing an increase in the settling rate. Poor clarity is also associated with these higher settling rates at the low flocculant dosages supporting this perspective. The poor clarity results from the associated higher velocities pulling the finer particles upwards decreasing the clarity of the liquor. The lower % boehmite blends have better compaction even though the flocculant dosage is increasing because of the size of Boehmite particles.

It is recommended that a viscosity modifier be added for the effective processing of these mud slurries and be added near the rake blades after flocculation. Addition to the center feed well would increase the rate of consolidation of the flocculated solids and reduce the viscosity. However, optimal viscosity reduction is observed at the rake level [9].

4. Conclusion

Alumina refineries will require modifications of hardware and operating methods if they are to process the lower grades of bauxite available in Jamaica. These modifications include utilizing high-rate vessels for thickeners/settlers and washers, to accommodate the increased volume from the higher mud load generated, as well as the increased dilution necessary to achieve lower solids. Eductor technology should also be utilized in the feed well to the vessels to facilitate higher dilution (up to 3–4 times) as necessary to process the mud residue. A viscosity or rheology modifier should be used to help process the slurries which will allow for increased solids content, increased pumping capabilities and reduced torque on the rake blades.

5. Acknowledgments

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