A Comparative Study to Assess the Efficiency of Wet Beneficiation Techniques for Treatment of Low-Grade and High-Grade Bauxite Ore

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Abstract

Bauxite is the basic raw material of aluminium used to extract alumina in Bayer's process. With the huge demand and the rapid development of the global alumina industry, bauxite consumption is rising and has reached more than 160 million tonnes per year. With such a high demand for aluminium, it is becoming more difficult to meet the consumption due to the gradual global decline of high-grade bauxite resources. In the current market scenario, treating bauxites containing more than 5% reactive silica ($SiO2$) is generally considered uneconomic due to excessive soda consumption in Bayer's process. The present study is conducted to examine the influence of the wet beneficiation process in the pre-treatment of low-grade and high-grade bauxite ores and a comparative analysis of the results obtained regarding alumina recovery and silica reduction. For this study, High-Grade (HG) and Low-Grade (LG) bauxite ore samples were collected from different bauxite mines of the East Coast region and subjected to wet beneficiation. Comparative chemical analysis of the before and after beneficiation samples revealed the wet beneficiation process to be significantly effective in the pre-treatment of LG bauxite samples with an average increment of 10.84% in the alumina content and 18.38% average reduction in silica after wet beneficiation.

Keywords: *Alumina, Bauxite, Beneficiation, Recovery*

1.0 Introduction

Bauxite is a relatively high aluminium-content sedimentary rock, the primary source of aluminium from alumina. Bauxite consists mostly of aluminium minerals like gibbsite, boehmite and diasporic minerals, along with other oxides of iron like hematite (Fe_2O_3) and goethite ($FeO(OH)$). The aluminous clay minerals are also associated with bauxite ore in kaolinite and small amounts of anatase and ilmenite. In addition, it contains several kinds of impurities, such as iron, titanium, and silica, which directly affect the quality and quantity of aluminium. The compounds of iron and titanium are insoluble in caustic solutions, and because of the high percentage of these contents, more red mud is generated during the process. The silicon compounds are present in the form of quartz and kaolin in bauxite and dissolve in caustic soda used in the digestion process, but bauxite, comprising substantial amounts of Silica, has the potential to be tough to treat economically.

Bauxite ore containing more than 5% reactive silica is considered uneconomic for processing due to excessive soda consumption in Bayer's process. Research is being done in most bauxite-producing countries to develop cheap and innovative bauxite beneficiation processes. Research in India also crosses international lines but is confined to the laboratory. The Indian Bureau of Mines (IBM), Nagpur, the Jawaharlal Nehru Research

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Development and Design Center (JNARDDC), Nagpur and the Regional Research Laboratory (RRL), Bhubaneswar, all claim to have lab-scale processes that are ready to be upscaled to pilot plant levels. IBM has done numerous beneficiation tests, using different methods, on various bauxite ore deposits found in India. The RRL claims to have developed a beneficiation process to produce non-metallurgical grade bauxite, whereas the JNARDDC says it has processes for both metallurgical and non-metallurgical grades. Of the three, only JNARDDC is still actively researching bauxite beneficiation[1].

Hence, it is always desired to reduce silica content to the maximum extent possible by pre-treatment of bauxite ores before Bayer's process feeding, dry crushing and screening are the most widely used pre-treatment methods of silica reduction, whereas other methods are rarely used by the industries because of high processing cost. Declining resources of bauxite ore and increasing demand by alumina users underlines the importance of the present study to find ways of processing low-grade high-silica bauxite ores other than dry crushing and sieving.

2.0 Methods of Mineral Beneficiation

The mineral resources as mined, or the 'run-of-mine ores' or 'raw ores', are not uniform in their composition of constituents, may be too coarse and/or unstable in size, and in many cases, too poor in grade to be utilized for sustaining our plant process. Mineral processing is based on separation processes and is involved in performing and description of separations, as well as their analysis, evaluation, and comparison. Mineral processing involves four types of operations:

1. Comminution
2. Sizing and Screening
3. Dewatering
4. Concentration.

2.1 Comminution

Comminution processes are generally preliminary to the separation processes in mineral processing. The first objective of comminution is "liberation". Liberation is the process of unlocking composite minerals in the raw ore into more independent particles, and without this process, we cannot collect wanted components. The second objective of comminution is to adjust the size of mineral particles to adapt to the optimum size for the successive separation processes. To avoid excessive cost for grinding, some of the separation processes may be taken up in the middle of the course and fine size reduction stages. Many principles of separation methods and techniques have been developed for the separation of valuable minerals from unwanted minerals/impurities. These separation methods are based on the differences among the physical properties of various minerals such as shapes, specific gravity, surface chemical properties, electromagnetic susceptibility, susceptibility to size reduction etc[2,3].

The primary objective of the beneficiation process is to reduce the silica content in the ore, as the latter reacts with caustic soda during the digestion step to precipitate out as insoluble sodium aluminium silicates. This salt is eliminated from the process along with the insoluble iron and titanium oxides in red mud, consequently entailing the loss of valuable alumina and caustic soda from the process.

2.2 Crushing, Screening, and Scrubbing

Crushing, screening and scrubbing are very effective in reducing silica in the bauxite feed material if the silica is preferentially concentrated in the smaller particle size fractions or fines. A study conducted by Massola *et al.,* stated that unwanted silica percentage in bauxite must be reduced through beneficiation e.g. flotation dry milling before feeding the material to the Bayer process[4]. Groudeva and Groudev also examined the specific use of "Silicate" bacteria to remove silicates from bauxite and upgrade the Al_2O_3 in low-grade bauxite, which can be used in the Bayer Process but still to be tested on commercial level[5].

It is believed that the removal of residual kaolinite from the washing process is possible through physical and/ or physicochemical processes, such as washing and screening, flotation of gangue minerals or mechanochemical activation, increasing the mass ratio between available Al_2O_3 and reactive SiO_2 (A/S ratio). Liu *et al*, Wang *et al.,* and Xu *et al.,* studied the visibility of increasing the alumina/silica ratio of Chinese diasporic bauxite by removing quartz silica through the flotation process. Flotation is particularly suited to diasporic ores in which there is sufficient liberation of alumina from

silica minerals, and the silicate minerals are of a particle size suitable to flotation (10-200 μm)[6-8]. This technology is not expected to be useful for lateritic bauxites where the silicate and alumina minerals cannot be sufficiently liberated to achieve good upgrading and recoveries. A good explanation of liberation to beneficiation options is given by Solymar and Madai *et al*[9].

2.3 Gravity Separation

Gravity separation technique for beneficiation has been used to target valuable by-products from the reprocessing of Bayer residue[10] examined the possibility of separating titanium minerals (rutile and ilmenite) from Bayer residue. The work was successful partly because of the high density of the titanium minerals, which would be heavier than sodalite, goethite and quartz but lighter than hematite[11]. There are many processes to upgrade the Al_2O_3 of low-grade bauxite by removing the silica content. By considering all the above literature, it was decided to examine the efficiency of the wet beneficiation process in the treatment of low-grade, high-silica-containing bauxite ores.

By considering all the above literature, it was decided to evaluate the efficiency of the wet beneficiation process for pre-treatment of high-grade and low-grade bauxite ores. A comparative analysis was made on the results obtained by quantifying the variations in silica and alumina content of the treated ore.

3.0 Materials and Methods

For this study, HG and LG bauxite ore samples were collected from different bauxite mines of the East Coast region. The methodology of the experiment is depicted in a flowchart, as shown in Figure 1.

These ore samples were crushed to -40 mm size to prepare composite samples. The weight of each collected sample was about 35 kg. Before starting the beneficiation process, representative samples of 5 kg were drawn and
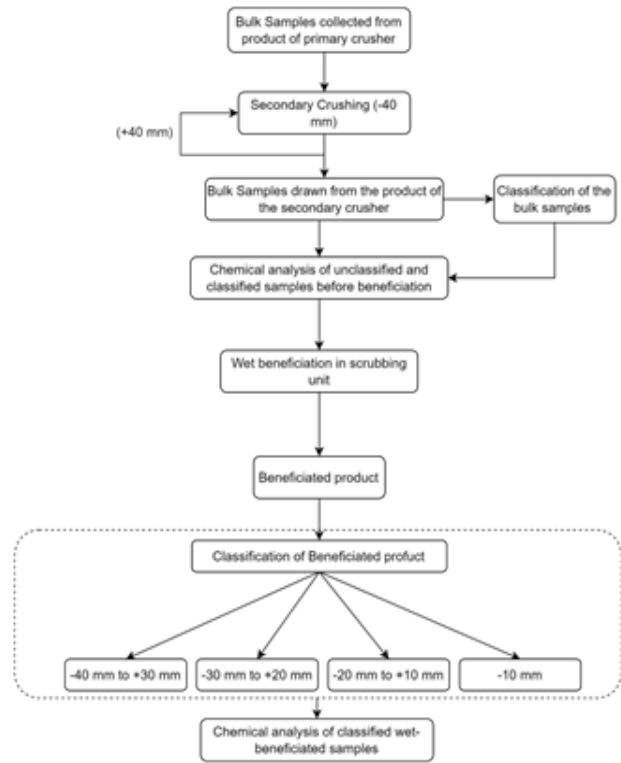

Figure 1. Flowchart of research methodology.

sent to the laboratory for chemical analysis to know the chemical composition of different minerals present in the bauxite. The result of the chemical analysis is presented in Table 1.

Each of the above-prepared samples was placed in a scrubbing unit with water to remove the contaminated fine-sized particles. Then, the scrubbed product was taken out and screened by different sizes available screens of 40mm, 30mm, 20mm, and 10mm size. The products of -40mm to +30mm, -30mm to +20mm, -20mm to +10mm and -10mm size samples were collected separately. The collected and screened samples were named as follows:

Table 1. Chemical composition of bauxite ore sample

Sl No.	Sample ID	Total Al_2O_3 (%)	Total SiO_2 (%)	LOI (%)	Fe_2O_3 (%)
1	HG	47.36	2.51	25.78	21.72
2	LG	36.26	10.34	20.46	28.57

1. Sample Id HG/1 and LG/1 refer to -40mm to +30mm size product.
2. Sample Id HG/2 and LG/2 refer to -30mm to +20mm size.
3. Sample Id HG/3 and LG/3 refer to -20mm to +10mm size, and
4. Sample Id HG/4 and LG/4 refers to -10mm size product.

Samples from these size fractions were dried first and subjected to chemical analysis to quantify the improvement in its alumina and reduction in silica content. During the wet sieving process, the percentage of material loss was also observed as the fines were dissolved and mixed with water.

4.0 Results and Discussions

As seen from Table 1, the total Al_2O_3 content of the studied sample of high-grade bauxite is 47.36% and low-grade bauxite is 36.26%, whereas the total SiO_2 content is 2.51% and 10.34% in high-grade and low-grade bauxite samples respectively. After the wet beneficiation process, the result of the chemical analysis of different size fractions for each of the samples is presented and discussed below one by one.

4.1 Test -1: Sample Id- HG

The result of the chemical analysis of composite sample Id HG is tabulated below in Table 2.

Table 2. Chemical analysis of sample HG having 47.36% Al_2O_3 and 2.51% SiO_2

Sl No.	Sample ID	Total Alumina (Al_2O_3, %)	Total Silica (SiO_2,%)
1	HG/1	49.11	1.79
2	HG/2	48.42	2.18
3	HG/3	46.01	3.21
4	HG/4	45.58	5.25

Table 3. Weighted analysis report of desired product of composite sample HG

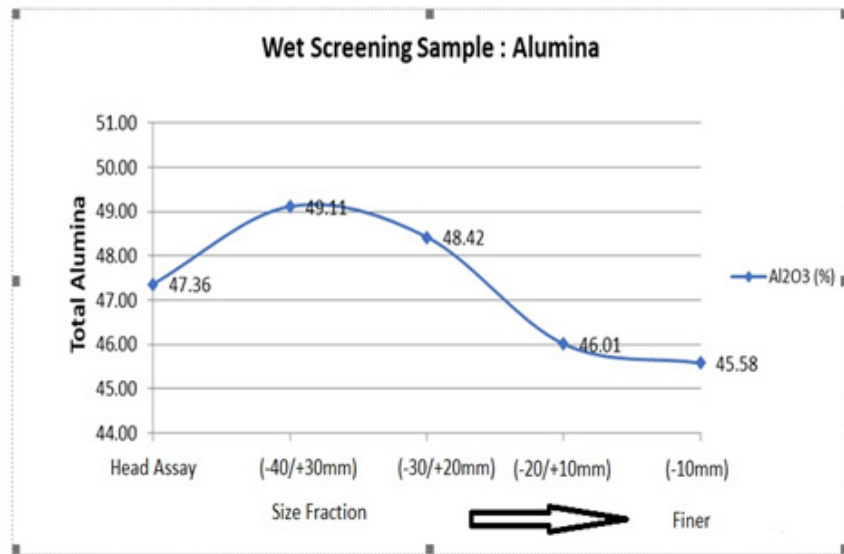| Sl. No.	Sizes	Sample No.	Wt. in Kg	Wt.%	Al_2O_3%	SiO_2%
1	Composite sample	HG	29.85	-	47.36	2.51
2	Test 1 -40/+30mm	HG/1	2.00	6.70	49.11	1.79
3	Test 1 -30/+20mm	HG/2	21.85	73.20	48.42	2.18
4	Test 1 (-20/+10 mm)	HG/3	5.15	17.25	46.01	3.21
5	Test 1 (-10 mm)	HG/4	0.70	2.35	45.58	5.25
4	Cumulative Weighted Average of +10mm product size		29.00	97.15	48.04	2.34

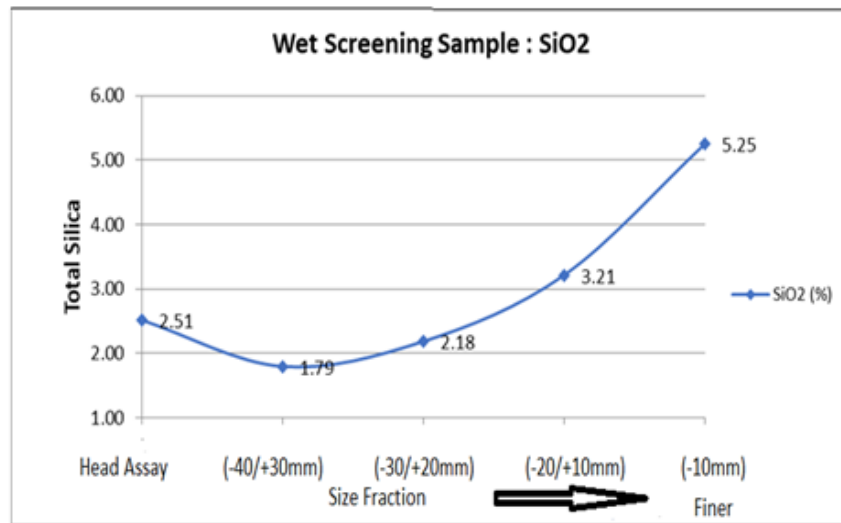**Figure 2.** The behaviour of total alumina Al_2O_3.

Figure 3. Behaviour of total silica (SiO_2).

The average quality and quantity of beneficiated product in terms of total alumina (Al_2O_3) and total silica (SiO_2) of the above composite sample id HG is tabulated as a weighted analysis report in Table 3.

The behaviour of total alumina (Al_2O_3) and total silica (SiO_2) after the beneficiation process of sample HG is graphically shown in Figure 2 and Figure 3.

The HG composite sample weighing 29.85 kg comprises 47.36% Al_2O_3 and 2.51% SiO_2. After crushing and wet sieving, a total of 29.70 kg (99.497 %) of feed composite sample material was retained while 0.150 kg (0.503%) of feed sample material was washed with process water. A large proportion of 73.20% and 17.25% (by weight) samples was retained within HG2 and HG3

size fractions, respectively. Smaller proportions of 6.70% and 2.35% (by weight) samples were retained within HG/1 and HG/4 size fractions, respectively (Table 2).

The total alumina content within each of the size fractions progressively varied from 49.11% for coarser size to 45.58% towards the finer size range. The alumina content is highest (49.11%) in the size fraction of HG/1, which constitutes only 6.70% (by weight). In all size ranges except for the size of HG/4, the alumina content is higher than 46% for all size fractions. Only 2.35% (by weight) of the total material comprises 45.58% of alumina content at the HG/4 size range.

Thus, while the feed composite sample comprised 47.36% Al_2O_3 and 2.51%, SiO_2 the % alumina in the HG/1 and HG/2 has been observed to be higher than the feed composite sample (Figure 1 and Figure 2). Similarly, the % silica in the HG/1 and HG/2 has been observed to be lower than the feed composite sample. Thus, this ore proportion lodged within HG/1 and HG/2, comprising 79.90% by weight is an enriched and qualitatively richer ore. Based on the % silica, HG/3 and HG/4 have silica content higher than the feed composite sample (Figure 1 and Figure 2). Thus 19.60% (by weight) of the sample has been associated with silica content higher than the feed composite sample indicating that total silica content is higher in finer size material.

The total silica content within each of the size fractions was observed to be 1.79%, 2.18%, 3.21% and 5.25% for size fractions of HG/1, HG/2, HG/3 and HG/4 respectively. The silica content is considerably high (5.25%) i.e., more than 200% silica content of feed bauxite for HG/4 which constitutes only 2.35% (by weight) of total material.

Considering the cumulative weighted averaging of size ranges starting from coarser towards finer, it was observed that % alumina (cumulative weighted average) varied through 49.11%, 48.45%, 48.04%, and 47.98% for size fractions of HG/1, HG/2, HG/3 and HG/4 respectively. Similarly, the cumulative weighted average of % silica varied through 1.79%, 2.15%, 2.34% and 2.40% for size fractions of HG/1, HG/2, HG/3 and HG/4 respectively. HG/4 exhibits a high %silica (5.25%), which is more than 200% silica content of feed bauxite, and it constitutes much less than only 2.35% (by weight) of total feed material. HG/4 thereby dilutes the assay content and adds to concentrated impurities within the cumulative material. HG/4 is therefore appropriated under insignificant contribution for the final ore enrichment. Considering the size fractions of HG/1, HG/2 and HG/3 a total of 97.152% by weight is the beneficiated ore having a cumulative average % alumina of 48.04% and cumulative average % silica of 2.34%. It is thus observed that the %alumina content has been enriched from 47.36% in the feed composite sample to 48.04% in the final beneficiated product. While a loss of 0.15 kg (0.503% by weight) occurred after the beneficiation process, 0.70 kg (2.35% by weight) was a lean ore with higher silica impurities.

The beneficiation process improved the alumina content by 1.44% over that of the feed composite sample and resulted in a lowering of silica content by 6.77% compared to the feed composite sample.

4.2 Test -2: Sample Id- LG

The result of the chemical analysis of composite sample ID LG is tabulated below in Table 4.

Table 4. Analysis report of different size fraction sample

Sl No.	Sample ID	Total Alumina (Al$_2$O$_3$%)	Total Silica (SiO$_2$%)
1	Composite sample LG	36.26	10.34
2	LG/1	38.79	7.02
3	LG/2	41.26	7.51
4	LG/3	35.82	13.62
5	LG/4	33.26	17.36

The average quality and quantity of beneficiated product in terms of total alumina (Al_2O_3) and total silica (SiO_2) of the above composite sample Id LG is tabulated below as a weighted analysis report in Table 5.

The behaviour of total alumina (Al_2O_3) and total silica (SiO_2) after the beneficiation process of sample LG is graphically shown in Figure 4 and Figure 5.

The LG composite sample weighing 30.50 kg comprises 36.26% Al_2O_3 and 10.34% SiO_2. After crushing and wet sieving, a total of 30.30 kg (99.344%) of feed composite sample material was retained while 0.20 kg (0.656%) of feed sample material was carried away with process water. A large proportion of 73.28% and 15.41% (by weight) samples was retained within LG/2 and LG/3 size fractions respectively. Smaller proportions of 8.03% and 2.62% (by weight) samples were retained within LG/1 and LG/4 size fractions respectively (Table 4).

The total alumina content within each of the size fractions progressively varied from 38.79%, 41.26%, 35.82%, and 33.26% down towards the finer size range. The alumina content is highest (41.26%) in the size fraction of LG/2 which constitutes 73.28% (by weight). Except for the
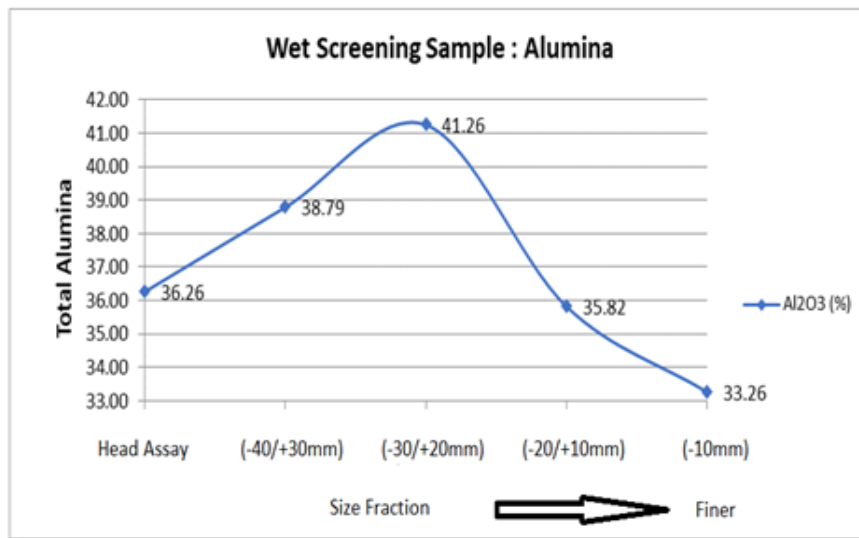

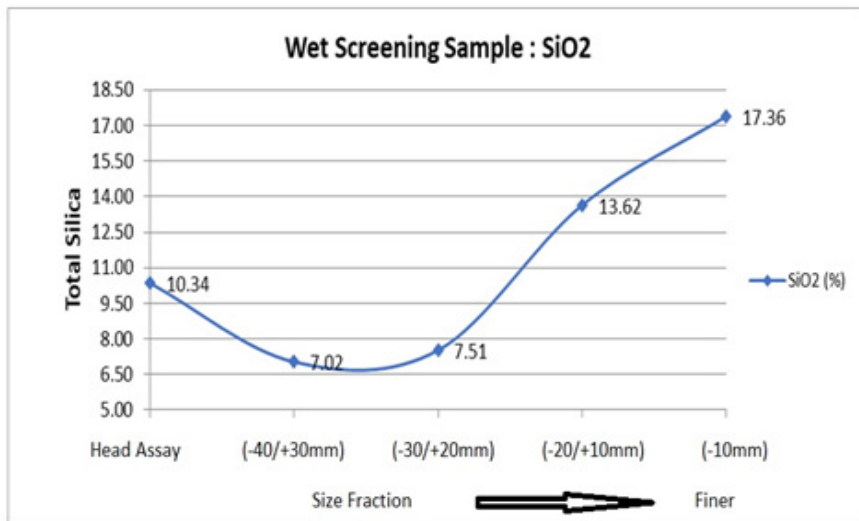**Figure 4.** Behaviour of total alumina (Al_2O_3).

Figure 5. Behaviour of total silica (SiO_2).

Table 5. Analysis report of desired product of composite sample LG

Sl. No.	Sizes	Sample No.	Wt. in Kg	Wt.%	Al_2O_3%	SiO_2%
1	Composite sample	LG	30.5	-	36.26	10.34
2	Test 2 -40/+30mm	LG/1	2.45	8.03	38.79	7.02
3	Test 2 -30/+20mm	LG/2	22.35	73.28	41.26	7.51
4	Test 2 (-20/+10 mm)	LG/3	4.70	15.41	35.82	13.62
5	Test 2 (-10 mm)	LG/4	0.80	2.62	33.26	17.36
6	Cumulative Weighted Avg of +10mm of product size		29.50	96.72	40.19	8.44

size of LG/3 and LG/4, the alumina content is higher than the alumina content in the feed sample [Figure (3) and Figure (4)]. A larger portion (LG/2) comprising 73.28% (by weight) inherits 41.26% alumina content. Only 2.62% (by weight) of total material comprises of lower alumina content (33.26%).

The total silica content within each of the size fractions was observed to be 7.02%, 7.51%, 13.62%, and 17.36% for LG/1, LG/2, LG/3 and LG/4 respectively. The % silica in the LG/1 and LG/2 has been observed to be lower than the feed composite sample. Based on the % silica LG/3 and LG/4 has silica content higher than the feed composite sample (Figure (3) and Figure (4)). Thus 18.0% (by weight) of the sample has been associated with silica content higher than the feed composite sample indicating that total silica content is more in finer size fractions.

The cumulative weighted average of % alumina was 38.79%, 41.02%, 40.19%, 40.00% for size fractions of LG/1, LG/2, LG/3 and LG/4 respectively. Similarly, the cumulative weighted average of % Silica varied through 7.02%, 7.46%, 8.44%, 8.68% for LG/1, LG/2, LG/3 and LG/4 respectively.

LG/4 exhibits a high %silica (17.36%), which is about 168% more than feed bauxite and it constitutes only 2.62% (by weight) of total material. Also, LG/4 elevates the silica impurities within the cumulative material. LG/4, therefore, is excluded from further steps of enrichment. Thus, considering the size fractions of LG/1,

LG/2 and LG/3 a total of 29.50 kg (96.72% by weight) is the beneficiated ore having the cumulative average %alumina of 40.19% and cumulative average %silica of 8.44%. It is thus observed that the %alumina content has been enriched from 36.26% in the feed composite sample to 40.19% in the final beneficiated product. While a loss of 0.20 kg (0.656% by weight) occurred after the beneficiation process, 0.80 kg (2.62% by weight) was a lean ore with higher silica impurities.

From LG/1 to LG/4 the alumina content showed decreasing assay content and simultaneously the silica content continuously increased. The silica impurities are observed to be higher towards finer size fractions. The wet beneficiation process yielded a 10.84% higher alumina grade than that of the feed composite sample while also reducing 18.38% of the original silica content of the feed of the composite sample.

5.0 Comparative Analysis

The study indicated that in the case of high-grade bauxite ore, alumina content improved marginally to 48.04% from 47.36% of feed-grade bauxite which was only 1.44% of feed bauxite grade whereas, in the case of low-grade bauxite ore, alumina content improved significantly from 36.26% to 40.19% after beneficiation process which was about 10.84% as compared to initial feed bauxite grade ore. Similarly, in the case of silica

reduction after the beneficiation process, it was observed that only 6.77% silica content was reduced in the case of high-grade bauxite ore whereas in the case of low-grade bauxite, silica content reduction has been observed to be significant high which was about 18.38% as compared to feed grade bauxite. Kumar *et al.,* carried out detailed wet beneficiation studies on high silica content bauxite ore and could reduce the silica content significantly and achieved very good recovery of bauxite in the process. They also indicated that if reactive silica content in feed bauxite is more than 5% then this beneficiation process will work efficiently to reduce the silica content of feed bauxite[12]. Rao and Das also carried out characterization and beneficiation studies of low-grade bauxite ore and recommended to use of this beneficiation process for low-grade bauxite before feeding the same in Bayer's process to extract Alumina which reduces caustic soda loss in the process resulting in less cost of production[10]. Chaves *et al.,* carried scrubbing of feed in a drum scrubber, desliming in cyclones and screening of the scrubbed bauxite in a high-frequency screen and found the appropriate result[13].

During the above investigations, it is also noticed that there is some material loss during the beneficiation process either due to washing out of the finer size material with water or due to rejection of finer size material having high silica content which affects the efficiency of the process.

5.1 Statistical Inference

A statistical analysis was carried out to enhance the interpretation of the results of the wet beneficiation. The analysis was carried out using the ANOVA (Analysis of Variance) tool. At first, Two-way ANOVA without replication (at a 5% level of significance) was used to test the null hypothesis of no significant effect of size fraction on the total alumina and silica contents of the LG and HG samples. The results of the test have been summarized in Table 6.

From the observations of the two-way ANOVA carried out, there is no sufficient evidence to reject the null hypothesis and hence the effect of size fraction on the alumina and silica contents is not significant.

After this, another analysis was carried out to test the effectiveness of the wet beneficiation process. For this, one-way ANOVA (at a 5% level of significance) was carried out. Results of the chemical analysis of classified bauxite samples - before and after wet beneficiation, were compared to test the null hypothesis that the effect of wet beneficiation is not significant. The relevant results of the tests have been summarized in Tables 7 and 8.

Observing the results of the ANOVA test, there is sufficient evidence to reject the null hypothesis. It may be observed from the results that there is a significant difference in the alumina and silica contents of the LG samples before and after beneficiation with a P-value $\leq$ 0.05. Whereas the same is not significantly true for HG samples.

The potential reason behind improvement in the quality of LG bauxite with wet beneficiation may be attributed to the scrubbing out of the reactive silica particles leading to an improved assay and higher A/S ratio. In comparison to other beneficiation processes like floatation[10], and scrubbing of feed in the drum separator[13],

Table 6. ANOVA for testing the effect of size fraction on the alumina and silica contents

Two-way ANOVA (Without replication)						
Source of Variation	SS	df	MS	F	P-value	F crit
Size fraction	38.77	3	12.92	5.71	0.09	9.28
Grade	199.90	1	199.90	88.28	0.00	10.13
Error	6.79	3	2.26			
Total	245.46	7				

Table 7. ANOVA for testing the influence of wet beneficiation on alumina content of LG and HG samples

Alumina Content in LG samples - Before and After Beneficiation Sample Groups						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups (LG)	59.41	1	59.41	5.81	0.05	5.99
Within Groups (LG)	61.38	6	10.23			
Total	120.79	7				
Alumina Content in HG samples - Before and After beneficiation sample groups						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups (HG)	10.58	1	10.58	2.80	0.15	5.99
Within Groups (HG)	22.68	6	3.78			
Total	33.26	7				

Table 8. ANOVA for testing the influence of wet beneficiation on the silica content of LG and HG samples

Silica Content in LG samples - Before and After Beneficiation Sample Groups						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups (HG)	98.07	1	98.07	7.24	0.04	5.99
Within Groups (HG)	81.28	6	13.55			
Total	179.35	7				
Silica Content in HG samples - Before and After Beneficiation Sample Groups						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups (HG)	8.69	1	8.69	5.11	0.06	5.99
Within Groups (HG)	10.22	6	1.70			
Total	18.91	7				

the wet beneficiation process discussed in this article is simple and economical in terms of mechanization and implementation and may be adopted for small-scale operations as well even at the site of mining.

6.0 Conclusions

Investigations were carried out to examine the efficiency of the wet beneficiation process on pre-treatment of

both high-grade and low-grade bauxite ore samples of the East Coast bauxite mine. The result of experimental investigation reveals that the wet beneficiation process is suitable for pre-treatment of both low-grade and high-grade bauxite ore however in this study, this process has given better alumina recovery and reduction in silica in case of low-grade high silica content bauxite than that of high-grade low silica bauxite.

It is observed that in the case of high-grade bauxite ore only 1.44% alumina content increased whereas in the case of low-grade bauxite ore, alumina content significantly increased by about 10.84% after the wet beneficiation process and at the same time, silica reduction in case of high-grade bauxite ore is 6.77% whereas the same in case of low-grade bauxite ore is about 18.38% to that of feed bauxite. It means that in the case of treatment of high-grade low silica bauxite, the desired result cannot be achieved due to the nature of the occurrence of silica and reactive silica content in the bauxite ore.

Hence, it may be concluded from the above study that if the silica content in feed bauxite is above 5%, which refers to low-grade bauxite mostly, then the wet beneficiation process should be preferred for reducing the silica content. In the case of high-grade bauxite ore, where silica content is less than 5%, the above process will prove to be uneconomical and time-consuming.

7.0 References

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