

Original Article

# Beneficiation of Bauxite Ore Characterized by Low-Grade and High Silica Content Using Crushing and Scrubbing Technique

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**Abstract** - Bauxite is the primary ore of aluminum used to extract alumina in Bayer's process. It comprises hydrated forms of aluminum oxide (alumina) found in diverse structural configurations, dependent upon the hydration level and crystalline structure. Generally, four to six metric tons of bauxite raw materials are required to get one ton of aluminium metal, depending upon the quality of bauxite ore. The quality of bauxite ore governs the recovery of alumina from bauxite ore, i.e. total alumina content, silica content, as well as hematite and percentage of other impurities. Global bauxite reserves contain extensive quantities of ore, though certain reserves remain economically unviable because of higher levels of reactive silica, resulting in huge losses of caustic soda in the plant. With the depletion of high-grade ore reserves, there is a growing necessity to explore cost-effective processing methods for low-grade bauxite. This paper elucidates several beneficiation techniques, including crushing, size classification, washing, scrubbing, and gravity separation, aimed at reducing silica content and enhancing recoverable alumina content. The beneficiation process of crushing, screening and scrubbing has been performed on field samples. The samples chosen for the study mainly belong to high silica-containing low-grade bauxite ores which is generally considered as marginal subgrade ore.

**Keywords** - Alumina, Aluminum, Bauxite, Beneficiation, Silica.

## 1. Introduction

Primarily, bauxite ore exists in the form of aluminum oxide hydrates alongside impurities such as iron oxide, titanium dioxide, and silicon dioxide. Geologically, two major types of bauxite are recognized: lateritic bauxite and karst bauxites. Lateritic bauxites predominantly consist of aluminous silicate rocks, while karst bauxites originate from interbedded carbonate and aluminous silicate rocks. Predominant minerals found in lateritic bauxite include tri-hydrated gibbsite ( $\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$ ), monohydrate boehmite ( $\text{Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$ ), and oxide hydroxide diasporite ( $\alpha\text{-AlO}(\text{OH})$ ). Additionally, hematite and goethite are present as iron-bearing minerals. Kaolinite is the primary silicate mineral in lateritic ore, often found in association with goethite, while quartz is another common silicate mineral. Karst bauxite exhibits a distinct mineralogical composition due to formation at different weathering conditions. Because of variations in the mineralogy, the lateritic ores are more suitable in Bayer's process as they are easily digested compared to karst bauxites. Following steel, aluminum stands as the second most utilized metal globally. The increasing demand for aluminum poses challenges to alumina production, given the gradual global decline of high-grade bauxite resources. Hence, it is necessary

to evolve new methodologies for manufacturing aluminium metal from low-grade bauxite, aiming to reduce caustic and energy consumption and utilize the available low-grade bauxite deposits. Bauxite production is steadily rising to meet the increasing demand. The worldwide bauxite ore production is depicted in Figure 1. Alumina production is significantly influenced by bauxite quality, specifically the alumina content and presence of reactive silica, hematite, and other iron impurities. A major reason for the inefficiency of the Bayer process is the presence of impurities in bauxite. The industry lacks technically and economically viable methods for controlling and removing these impurities. Suppose ROM bauxite is of low quality and has higher silica content. In that case, the separation can be done by manual picking of high silica material after crushing and screening of low-grade bauxite, which is also economically feasible. This lower-cost process can increase the life of present bauxite mines having low grade bauxite reserves significantly and subsequently improve the economic and technical parameters of the plant. As per IBM notification no. C-284/3/CMG/2017, dated 24/05/2018, threshold value of Bauxite is amended as:

Alumina Content,  $\text{Al}_2\text{O}_3$  : 30% min.

Total Silica,  $\text{SiO}_2$  : 7% max.



At present, bauxites containing more than 5% reactive silica are not economical for processing in the plant due to huge soda loss in the process. To date, various research studies have mainly conducted experiments to reduce the high silica and iron content present in the low-grade bauxite ore at the laboratory level or pilot scale only. Hence, the applicability of the same is required to be ensured. Various mineral processing techniques are available to improve the quality of ROM ore. As the high-grade ores goes on diminishing globally due to the continuously increasing demand for aluminium by industry, more attention is required to develop new methodologies to process these low-grade bauxite. The huge quantity of waste generation in the Bayer Process can be reduced by pre-treatment of low grade Bauxite ores before it is subjected to Bayer’s treatment. This study primarily investigates the improvement in alumina content in the processing of high silica-containing low-grade bauxite ores by crushing and scrubbing processes.

**1.1. Beneficiation Process of Bauxite**

Generally, four to six tonnes of bauxite ore are required to produce one tonne of aluminium metal. Iron and titanium compounds, found as impurities in bauxite ore, remain insoluble in caustic solutions and transform into red mud after digestion. Silicon compounds in bauxite primarily manifest as quartz and hydrated double salts with alumina, like kaolin. During low-temperature digestion for alumina extraction from bauxite, a desilication step often occurs, where kaolinite dissolves, forming sodalite, a sodium aluminosilicate that is caustic insoluble.

This insoluble sodium aluminosilicate, consequently, separates into red mud. Increased silica content escalates soda consumption, thereby augmenting the cost of alumina production. Quartz dissolves slowly in caustic solutions, while other silica forms in bauxite may dissolve rapidly during digestion. The reactive silica, constituting about 90% of the total silica in the bauxite, readily reacts with caustic liquor at lower temperatures, forming a Desilication Product (DSP). About 1.2 tonnes of caustic soda are consumed for each ton of silica dissolved from bauxite during digestion, contributing to DSP formation. Soda demand for processing high-silica bauxites can amount to 20% of the cost of alumina production. The  $Al_2O_3/SiO_2$  mass ratio in bauxite ore holds economic significance. High-grade bauxite ore with an  $Al_2O_3/SiO_2$  ratio exceeding 10 can undergo direct processing without any pre-treatment process.

Conversely, a ratio below 8 denotes low-grade bauxite, necessitating pre-treatment before the Bayer process. Presently, bauxites containing over 5% silica render the Bayer process economically unfeasible. High silica content in bauxite processing increases soda consumption and decreases yield. Many bauxite reserves in India, with  $Al_2O_3/SiO_2$  ratios ranging from 4 to 6, pose challenges for alumina production via the Bayer process. Consequently, modern alumina industries seek processes to enhance the  $Al_2O_3/SiO_2$  ratio. Pre-treatment of high silica-containing ore is determined based on its geochemical characterization and impurity types. The primary objective of the pre-treatment process is to diminish silica content in the ore and improve valuable alumina content.

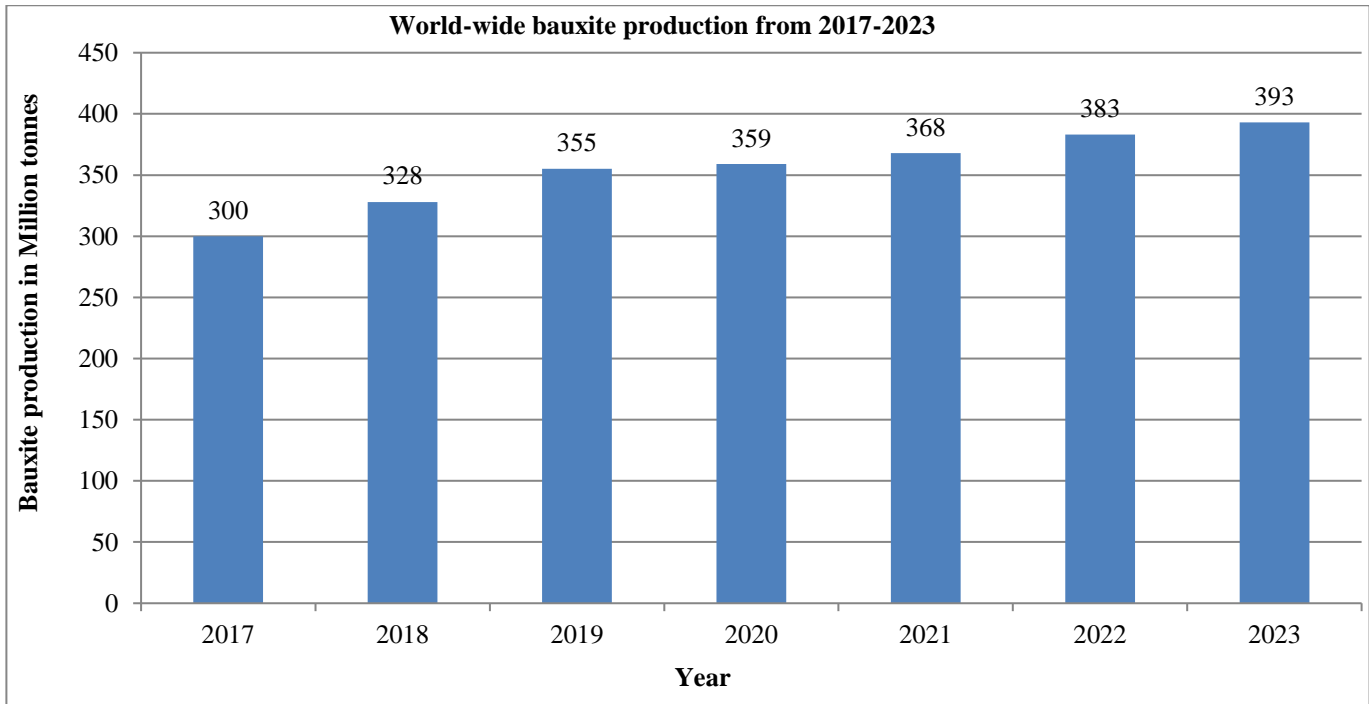


Fig. 1 Year-wise Bauxite production

### 1.2. Wet beneficiation by Crushing and Scrubbing

Crushing, screening, and scrubbing demonstrate significant efficacy in reducing silica content in the bauxite feed material, particularly when silica is concentrated in smaller particle size fractions or fines. As indicated by Massola [1], it is imperative to lower the unwanted silica percentage in bauxite through beneficiation methods such as flotation and dry milling before introducing the material to the Bayer process. Another approach involves incorporating hydroxy sodalite seed into the digestion chamber to enhance silica removal efficiency. Additionally, ultrasonic irradiation treatment has been employed to eliminate silica from the liquor spent, as demonstrated by McCormik et al. [2]. Various scale inhibitors for the DSP process have been developed and advocated within the industry to prevent silica precipitation from solution, as highlighted by Spitzer et al. [3]. Picaro [4] investigated the enhancement of DSP and TiO<sub>2</sub> minerals in the residue, while [5] explored the specific application of "Silicate" bacteria for silicate removal from bauxite and the enhancement of Al<sub>2</sub>O<sub>3</sub> in low-grade bauxite, although commercial-level testing is pending. It is believed that residual kaolinite removal from the washing process can be achieved through different physicochemical and/or physical processes, such as washing, screening, froth flotation of the gangue, or mechano-chemical activation, thereby increasing the mass ratio between available Al<sub>2</sub>O<sub>3</sub> and reactive SiO<sub>2</sub> (A/S ratio). Flotation is particularly suitable for diasporic ores with a sufficient degree of liberation of the valuable alumina from the silica minerals at suitable particle sizes for flotation (~10–200 μm) [6-8]. Solymer [9] provides a comprehensive explanation of liberation concerning beneficiation options.

### 1.3. Gravity Separation

The utilization of gravity separation as a beneficiation technique has been applied to isolate valuable by-products during the processing of residue from Bayer's process. Rao et al. [10] explored the feasibility of separating the titanium minerals from the Bayer residue. The endeavor proved successful, partly owing to the higher density of the titanium minerals, rendering them lighter than hematite but heavier than goethite, quartz, and sodalite. Various methods exist for enhancing the Al<sub>2</sub>O<sub>3</sub> content of low-grade bauxite by eliminating silica. After reviewing the literature, it was determined that assessing the effectiveness of wet beneficiation processes for treating low-grade bauxite ores with high silica content was warranted.

## 2. Materials and Methods

### 2.1. Sample Collection and Laboratory Analysis

For this study, four low-grade, high-silica-containing bauxite samples were collected from different bauxite mines in Odisha. A petrographic study was carried out to understand the mineral composition of bauxite. The texture of the ore was found to be matrix-supported with variations of mineral content in the sample. Some oolites and pisolites were also seen in the sample.

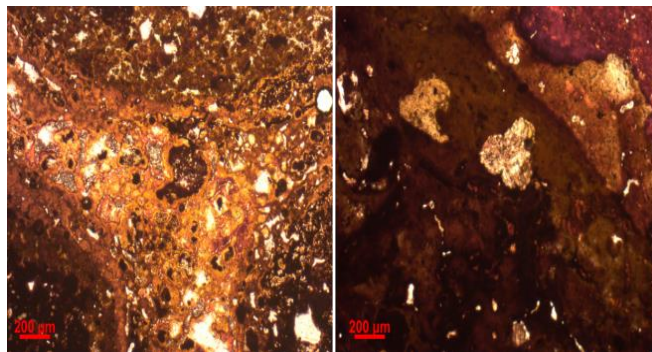


Fig. 2 Photomicrographs of Bauxite samples

Table 1. Chemical composition of low-grade Bauxite samples

Sl No.	Sample ID	Total Al <sub>2</sub> O <sub>3</sub> , (%)	Total SiO <sub>2</sub> (%)	LOI, (%)	Fe <sub>2</sub> O <sub>3</sub> , (%)
1	ODB-1	41.84	5.14	22.62	25.42
2	ODB-2	41.20	6.39	22.38	26.31
3	ODB-3	39.21	7.82	21.28	26.72
4	ODB-4	38.28	8.18	21.13	27.75

The oolites and pisolites matrix consists of a combination of aluminium-hydroxides, Iron-oxy-hydroxides and Kaolinite. All the available content other than aluminium in bauxite samples was treated as impurities and needed to be separated before use in the alumina plant to extract alumina else the process would not be economically viable. The images of studied bauxite samples are given above.

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 work, representative samples of 5kg were drawn and sent to the laboratory for chemical analysis. The result of the chemical analysis is presented in Table 1. It indicates that all these samples belong to the low-grade high silica category. As seen from Table 1, the total Al<sub>2</sub>O<sub>3</sub> content of the studied samples varied from 41.84% to 38.28%, whereas the total SiO<sub>2</sub> content ranged from 5.14% to 8.18%.

### 2.2. Wet Beneficiation and Screening

Each of the above prepared samples was placed in a scrubbing unit containing water for removal of the fine size contaminated particles. Then the scrubbed product was screened by different sizes available screen 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. In this way, the following group of samples were prepared for all the above categories of ores taken for the study:

- WB-1 (-40mm to +30mm)
- WB-2 (-30mm to +20mm)
- WB-3 (-20mm to +10mm)
- WB-4 (-10mm)

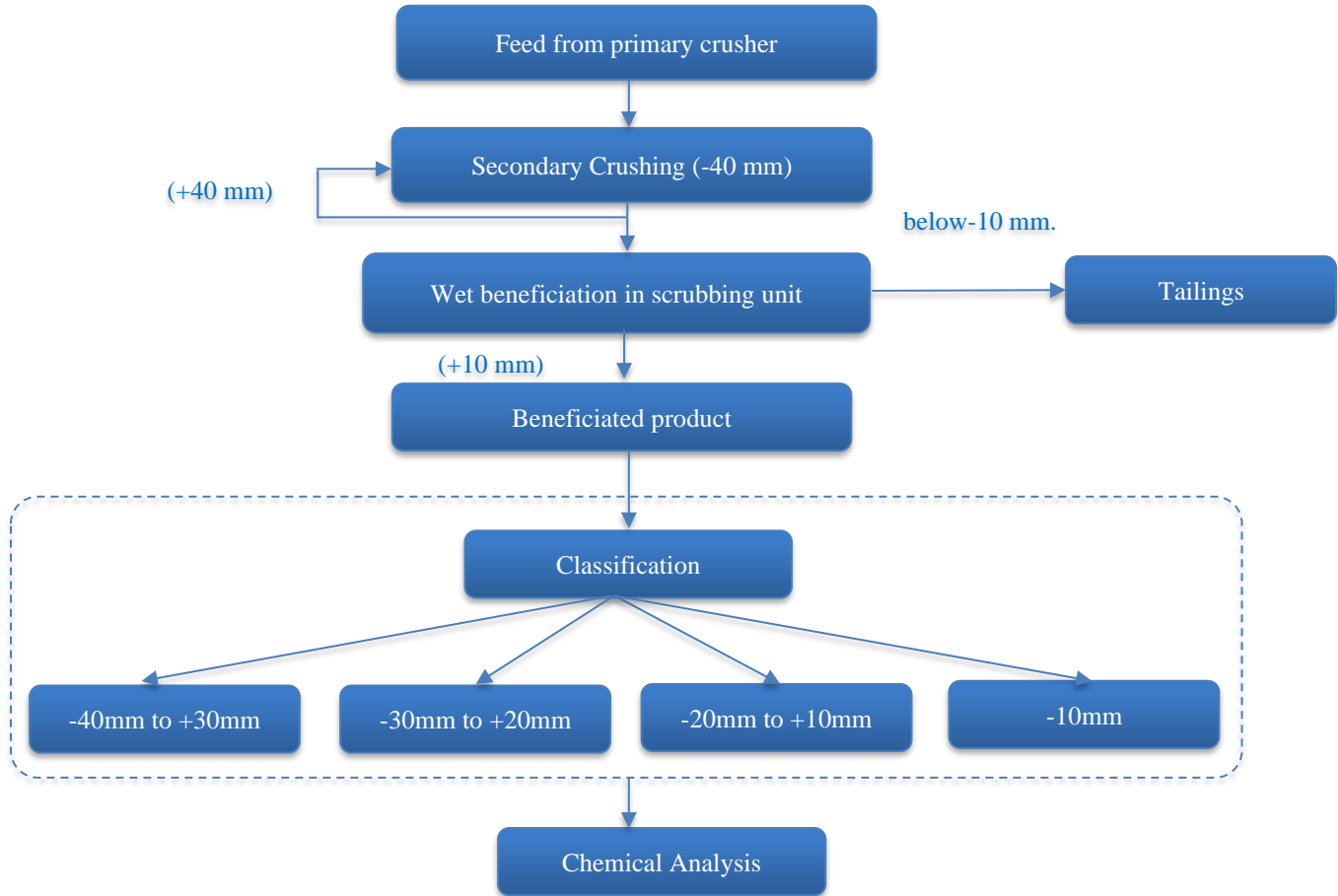


Fig. 3 Main steps involved in the wet beneficiation process and further chemical analysis

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. The flow chart shown in Figure 3 depicts the main steps involved in the wet beneficiation process and further chemical analysis.

**2.3. Quality Analysis**

The data obtained from the weighted chemical analysis of the classified wet beneficiation product has been summarized in Table 2. After crushing and wet sieving, significant portions of the initial sample materials were retained, ranging from 99.19% to 99.656% (by weight). The retained material varied within different size fractions, with WB2 and WB3 consistently retaining larger proportions, ranging from 74.76% to 76.29% (by weight). Minor portions were carried away by process water, ranging from 0.344% to 0.81%. Notably, WB1 and WB4 size fractions generally comprised smaller proportions, ranging from 2.34% to 7.41% by weight. Further, the samples ODB-1, ODB-2, ODB-3, and ODB-4, weighing 30.35 kg, 30.70 kg, 29.10 kg, and 29.90 kg, respectively, were analyzed for Al<sub>2</sub>O<sub>3</sub> and SiO<sub>2</sub> content.

Table 2. Summary of weighted chemical analysis of the classified product of wet beneficiation

Sample No.	Wt. in Kg	Wt.%	Al <sub>2</sub> O <sub>3</sub> %	SiO <sub>2</sub> %
<b>ODB-1</b>				
WB-1	2.25	7.41	44.98	3.09
WB-2	22.7	74.79	45.71	3.84
WB-3	4.5	14.83	40.27	7.86
WB-4	0.75	2.47	36.01	10.22
<b>ODB-2</b>				
WB-1	2.05	6.7	45.86	4.12
WB-2	22.95	74.7	45.19	4.72
WB-3	4.65	15.27	41.04	7.78
WB-4	0.8	2.63	36.64	12.22
<b>ODB-3</b>				
WB-1	1.95	6.7	44.01	4.72
WB-2	22.2	76.29	42.42	5.82
WB-3	4.1	14.09	39.71	8.13
WB-4	0.75	2.58	34.81	15.14
<b>ODB-4</b>				
WB-1	2.05	6.86	42.01	5.02
WB-2	22.8	76.25	42.14	6.07
WB-3	4.2	14.05	37.16	7.61
WB-4	0.7	2.34	34.64	15.88

**Table 3. Quality analysis for different sample types under all four size fractions**

Total Al <sub>2</sub> O <sub>3</sub> content (%)				
Samples	Size fractions			
	WB1	WB2	WB3	WB4
ODB-1	44.98	45.71	40.27	36.01
ODB-2	45.86	45.19	41.04	36.64
ODB-3	44.01	42.42	39.71	34.81
ODB-4	42.01	42.14	37.16	34.64
Total SiO <sub>2</sub> content (%)				
Samples	Size fractions			
	WB1	WB2	WB3	WB4
ODB-1	3.09	3.84	7.86	10.22
ODB-2	4.12	4.72	7.78	12.22
ODB-3	4.72	5.82	8.13	15.14
ODB-4	5.02	6.07	7.61	15.88

The results of the chemical analysis have been further rearranged in the above Table 3 for easy interpretation.

**2.4. Statistical Analysis**

To comprehensively understand the post beneficiation changes in TAA and silica contents of the four samples, a detailed statistical analysis was conducted. For this, a two-way analysis of variance (ANOVA-Two factor without replication) test of significance was conducted with a

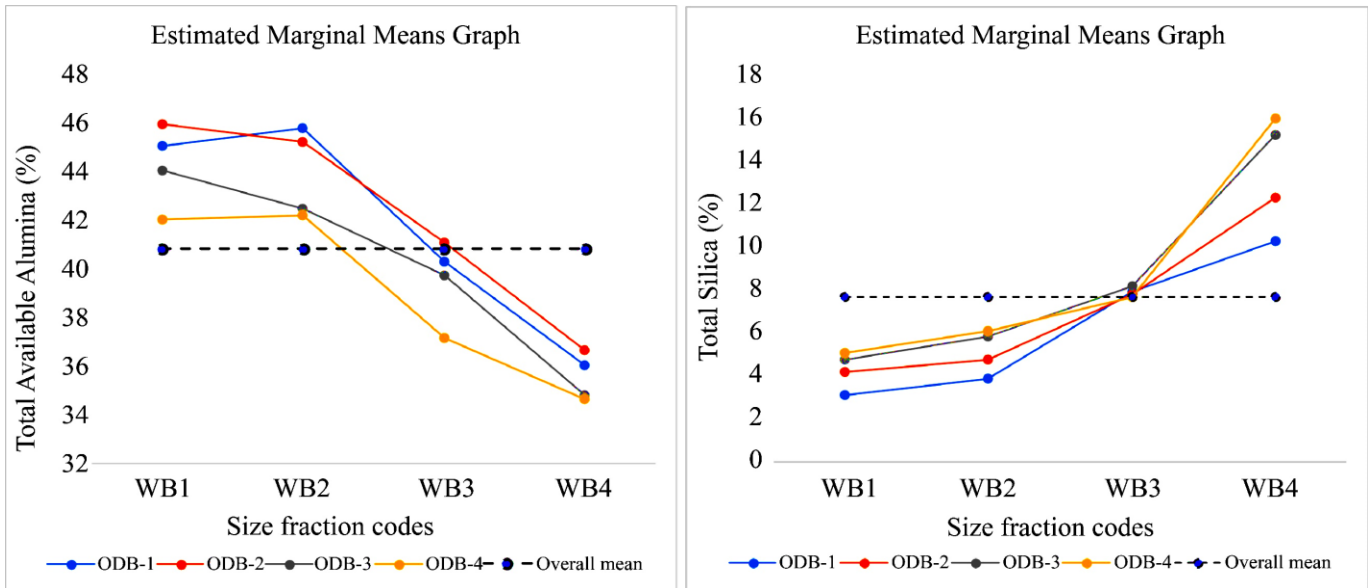
randomized block design at a 5% level of significance ( $\alpha=0.05$ ). The factors considered were the size fractions and the blocking variable was the sample type with the four different random blocks, ODB-1 through ODB-4. The results of the ANOVA have been tabulated below. To quantify the influence of feed size on the efficiency of the wet beneficiation process, an alternative hypothesis claiming a significant difference in the means of total alumina and silica content among the four size fractions under different sample types was tested against the null hypothesis that there is no significant difference among the size fractions in either of the sample types. A graph showing estimated marginal means was also plotted (Figure 4) to get visual insights on the variation of total alumina and silica contents with variation in size fractions for different sample types.

**Table 4. Summary of Two-way ANOVA (without replication) carried out for Total Alumina content**

ANOVA-Two way (without replication) for Total Alumina content						
Source of Variation	SS	df	MS	F	P-value	F crit
Sample type	25.60	3	8.534	18.89	0.000318	3.86
Size fraction	201.82	3	67.27	148.93	5.48E-08	3.86
Error	4.06	9	0.45	-	-	-
Total	231.49	15	-	-	-	-

**Table 5. Summary of Two-way ANOVA (without replication) carried out for total silica content**

ANOVA-Two way (without replication) for Total Silica content						
Source of Variation	SS	df	MS	F	P-value	F crit
Sample type	15.12095	3	5.040317	4.099967	0.043307	3.862548
Size fraction	203.13165	3	67.71055	55.07809	4.1E-06	3.862548
Error	11.0642	9	1.229356	-	-	-
Total	229.3168	15	-	-	-	-



**Fig. 4 Estimated marginal means graph for total available alumina and total silica contents**

### 3. Results and Discussions

The results of the ANOVA test revealed interesting facts about the sources of variation in the total alumina and silica percentages. In both the tables, it can be observed that both the sample type and the size fraction are a significant source of variations with a p-value  $\leq 0.05$  and an F-ratio  $> F_{critical}$  at  $\alpha=0.05$ . This led to the inference that there is sufficient evidence to reject the null hypothesis. Further, it can be observed that for both % Alumina and % Silica contents, the size fraction is the most significant source of variation with more than 85% share in the explained variance.

From the estimated marginal means graph, it can be observed that a marked difference exists in the post-beneficiation alumina content in the coarser size fractions. The mean alumina content was found to be reduced acutely with the feed size, from 44.21% in the WB-1 size to 35.52% in the WB-4 size fraction. It can also be observed that as the feed size gets finer, the difference in the alumina content gets less significant. A significant difference in the alumina content exists between samples ODB-1 and ODB-4 and between ODB-2 and ODB-4. Among ODB-3 and ODB-4, a significant difference exists in the size fraction WB-1 and WB-3. However, among samples ODB-1 and ODB-2, not much difference in the alumina content was observed and an interaction effect has also been found among the factors and blocking variables.

On the other hand, the difference in silica content of the beneficiated product is less significant among the samples at the coarser size fractions and appears prominent at the WB-4 size range. Whereas, the mean reactive silica content can be observed to be widely varying among the size fractions, with 4.23% in the WB-1 range to 13.36% in the WB-4 size fraction. This indicates that the total silica increases significantly in finer feed size in all four samples. Kumar et al. [11] also carried out wet beneficiation studies on a high silica bauxite and concluded that silica content could be reduced significantly. They also revealed that total alumina in finer size fraction material is lower than coarser size fraction, and at the same time, total silica increases in finer size fraction. A comparison between the reactive silica contents of the feed and the product of the wet beneficiation process has been summarized in Table 6.

It may be observed that in the product size fraction WB-1 and WB-2, there is a significant drop in the silica content for all four samples as compared to the feed, whereas in the WB-3 and WB-4 size range, the silica content has prominently elevated after the beneficiation. However, with a higher alumina content, the WB-3 size range is economical up to an extent in the case of samples ODB-1, ODB-2, and ODB-3, but in the case of ODB-4, even the WB-3 size range becomes uneconomical. Thus, it may be inferred that enrichment is observed for alumina till the size range of WB-3 (-20mm to +10 mm).

**Table 6. Comparison of total reactive silica content in feed and product of the Wet beneficiation process**

Total reactive silica content (%)				
	ODB-1	ODB-2	ODB-3	ODB-4
Feed	5.14	6.39	7.82	8.18
WB-1	3.09	4.12	4.72	5.02
WB-2	3.84	4.72	5.82	6.07
WB-3	7.86	7.78	8.13	7.61
WB-4	10.22	12.22	15.14	15.88

Moreover, since the silica content in the WB-4 size of the beneficiated product is very high as compared to a feed of composite bauxite material in all four representative samples, it is advantageous to discard the finer fraction size of -10 mm material to avoid dilution in the assay content and restrict the addition of concentrated impurities which leads to increased consumption of caustic soda in the Bayer’s process of alumina extraction.

### 4. Conclusion

In this research work, an experiment of wet beneficiation was conducted with four different low-grade Indian bauxite ore samples to determine the post-beneficiation extent of reduction in silica for minimizing caustic soda consumption. The methodology of wet beneficiation essentially comprised of crushing, scrubbing, and screening of representative samples to remove the silica content present in feed grade bauxite.

Detailed chemical analysis of the feed was carried out to determine the alumina and silica contents. The product of wet beneficiation was further classified into four different size fractions: WB-1 (-40mm to +30mm), WB-2 (-30mm to +20mm), WB-3 (-20mm to +10mm) and WB-4 (-10mm) and were collected separately. The detailed chemical and statistical analysis of the classified wet beneficiation product revealed a noticeable improvement in the total alumina content while a significant reduction in reactive silica content, pointing towards the effectiveness of the wet beneficiation process for pre-treatment of low-grade bauxite ores before extraction of alumina. This pre-treatment will not only improve the efficiency of the plant but will also result in better plant economics due to alumina quality enhancement.

Based on the results and discussions of the experiment, the following specific conclusions can be drawn.

- For both % Alumina and % Silica contents, the size fraction is the most significant source of variation, with more than 85% share in the explained variance.
- The mean alumina content was found to be reduced acutely with the feed size, from 44.21% in the WB-1 (-40mm to +30mm) size range to 35.52% in the WB-4 (-10mm).
- The mean reactive silica content was observed to be widely varying among the size fractions, with 4.23% in

the WB-1 (-40mm to +30mm) size range to 13.36% in the WB-4 (-10mm).

- A comparison between the reactive silica contents of the feed and the product of the wet beneficiation process revealed that a significant enrichment is observed for alumina till the size range of WB-3 (-20mm to +10 mm).
- The silica content in the WB-4 size of the beneficiated product is very high as compared to a feed of composite bauxite material in all four representative samples. It is

advantageous to discard the finer fraction size of -10 mm material to avoid dilution in the assay content.

In view of the above experiments, it is concluded that the optimum feed size of material for the wet beneficiation process must be limited to +10 mm size only. The size of material less than 10 mm may be treated as rejects, as the silica content in all the samples for this size fraction was found to be greater than or equal to 8%.

## References

- [1] C.P. Massola et al., "Separation of Silica from Bauxite via Froth Flotation," *Minerals Engineering*, vol. 22, no. 4, pp. 315-318, 2009. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [2] P.G. McCormick, T. Picaro, and P.A.I. Smith, "Mechanochemical Treatment of High Silica Bauxite with Lime," *Minerals Engineering*, vol. 15, no. 4, pp. 211-214, 2002. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [3] Donald Spitzer et al., *MAX HT™ Sodalite Scale Inhibitor: Plant Experience and Impact on the Process, Essential Readings in Light Metals*, Springer, Cham, vol.1, pp. 832-837, 2016. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [4] T. Picaro et al., "Separation and Mineralogical Analysis of Bayer Red Mud," *Developments in Chemical Engineering and Mineral Processing*, vol. 10, no. 5-6, pp. 475-489, 2002. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [5] V.I. Groudeva, and S.N. Groudev, "Bauxite Dressing by Means of Bacillus Circulans," *Trav. Com. Int. Etude Bauxites, Alumine Alum*, vol. 13, no. 18, pp. 257-263, 1983. [[Google Scholar](#)]
- [6] Guangyi Liu et al., "The Role of Cationic Polyacrylamide in the Reverse Flotation of Diasporic Bauxite," *Minerals Engineering*, vol. 20, no. 13, pp. 1191-1199, 2007. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [7] Y. Wang et al., "Reverse Flotation for Removal of Silicates from Diasporic-Bauxite," *Minerals Engineering*, vol. 17, no. 1, pp. 63-68, 2004. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [8] Zhenghe Xu, Verne Plitt, and Qi Liu, "Recent Advances in Reverse Flotation of Diasporic Ores—A Chinese Experience," *Minerals Engineering*, vol. 17, no. 9-10, pp. 1007-1015, 2004. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [9] Károly Solymár, Ferenc Mádai, and Dimitri Papanastassiou, *Effect of Bauxite Microstructure on Beneficiation and Processing, Essential Readings in Light Metals*, Springer, Cham, pp. 37-42, 2016. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [10] M.B.S. Rao et al., "Beneficiation of Titanium Minerals from Sand Rejects of an Alumina Refinery Plant by Gravity Separation," *Powder Handling and Processing*, vol. 8, no. 4, pp. 351-354, 1996. [[Google Scholar](#)]
- [11] Mukesh Kumar, Bimalananda Senapati, and C. Sateesh Kumar, *Beneficiation of High Silica Bauxite Ores of India an Innovative Approach, Light Metals 2013*, Minerals, Metals & Materials Series, Springer, Cham, pp. 187-190, 2016. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]