INTEGRATED MINERALOGICAL CHARACTERIZATION AND GRINDABILITY ASSESSMENT OF AJABANOKO IRON ORE (KOGI STATE, NIGERIA) FOR BENEFICIATION OPTIMIZATION

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DOI10.51459/jostir.2026.2.2.0301

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ABSTRACT

The knowledge of ore mineralogical composition, particle size distribution, and ore grindability is essential for successful beneficiation in mineral processing. The mineralogical and comminution behavior of Ajabanoko iron ore was studied by integrating X-ray diffraction (XRD), scanning electron microscopy (SEM-EDS), petrographic analysis, and Bond work index determination. X-ray fluorescence (XRF) analysis indicated that the ore contains 61.05% Si and 34.28% Fe. XRD results showed quartz as the most abundant mineral phase, and hematite and minor goethite were the major iron-bearing minerals. The petrographic analysis indicated a complex mineralogical assemblage of quartz, feldspar, mica, and iron oxides with moderate grain interlocking, whereas SEM-EDS analysis revealed hematite particles closely associated with ingrown quartz and aluminosilicates, suggesting a complex mineralogy. The ore had theoretical and actual liberation sizes of -250+180 μm and -1200+1000 μm, respectively, and a work index of 14.80 kWh/t. The calculated energy required for grinding the Ajabanoko iron ore was 7.47 kWh. The mineralogical and textural features had a significant impact on the comminution properties of Ajabanoko iron ore. Based on the association of hematite-quartz, the grinding conditions were essential for ensuring its complete liberation with minimum grinding energy.

Keywords: Bond Work Index (BWI), Mineral Liberation, Grindability, Mineralogical Characterization

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History
Received: 24-04-2026
Accepted: 15-06-2026
Published: August, 2026

https://www.futa.edu.ng

JOSTIR
JOURNAL OF SCIENCE, TECHNOLOGY AND INNOVATION RESEARCH
https://jostir.futa.edu.ng

1. | Introduction

Crushing and grinding operations used to liberate minerals from gangue in an ore are known as comminution in mineral processing. The stage is proven to be the highest-energy-consuming stage in processing plants, accounting for 40-50% of the total energy requirement of the processing stage (Wills *et al.,* 2015). Comminution is the most energy-intensive process in mineral beneficiation operations, therefore efficient comminution can help reduce operational costs and environmental impacts (Wills *et al.,* 2015).

Bond Work Index (BWI) is a widely adopted index of ore grindability that indicates the energy required to reduce the ore to a specified particle size during the comminution process. The BWI, an index of ore grindability, is commonly used to estimate the energy requirements of comminution processes, and is widely used in the design, selection, and optimisation of grinding circuits in mining and mineral processing plants (Kolev *et al.,* 2021). Although ore hardness is frequently

used as an important indicator of grindability, other ore properties, such as mineral composition, grain-size distribution, texture, and the structural features of the ore matrix, also play a role in determining the ease or difficulty of size reduction. Gbadamosi *et al.* (2021) reported that ores of the same hardness may have different grindability properties as a result of variation in mineralogical composition and textural structure. The relationship between mineralogy and ore comminution has received considerable attention in mineral processing research. Similar research by Roy *et al.* (2020) reported that iron ores commonly contain intergrowths of hematite and quartz, which can complicate mineral liberation and influence grinding requirements. In addition, the presence of soft gangue minerals embedded in relatively hard ore, such as hematite, may cause differential grinding behaviour, resulting in a broad particle size distribution and increased generation of ultrafine particles (Bouchard *et al.,* 2019). These observations reveal that mineralogical characteristics should be considered alongside comminution studies when evaluating the processing behaviour of an ore.

Various characterisation methods, such as X-ray fluorescence (XRF), X-ray diffraction (XRD), scanning electron microscopy coupled with energy-dispersive spectroscopy (SEM-EDS), and petrographic analysis, provide valuable insights into the chemical composition, mineral phases, and textural characteristics of an ore. XRD analysis reveals the mineralogical phases of an ore of interest, and XRF analysis reveals the elemental composition of the ore matrix. SEM-EDS provides detailed information in relation to the morphology of the sample, the element and its distribution, whereas the petrographic analysis provides information in relation to the grain size, mineral associations, interlocking of the sample or the ore (Wu *et al.,* 2019). This is important in mineral processing because the characterisations are significant for understanding the factors that control the behaviour of ores during comminution and beneficiation.

In Nigeria, a number of iron ore deposits from which iron ore for steel production will be sourced. However, many of these deposits have not yet been fully exploited due to a lack of in-depth characterisation and understanding of their comminution behavior (Thomas *et al.,* 2019). Since the region contains very limited information on the Ajabanoko iron ore deposit, an integrated study of the deposit is required, covering both mineralogy and comminution behaviour. While some studies have involved froth flotation and general mineralogical characterisation, none are detailed enough to correlate mineralogical properties with particle size distribution and grindability. Therefore, the current study aims to determine the particle size distribution and grindability of Ajabanoko Iron Ore using geochemical and mineralogical attribute analysis. In the study, along with sieve analysis and Bond work index determination, XRD, SEM-EDS, and petrographic analysis have been performed to provide a comprehensive understanding of the ore behaviour during comminution.

2. | Materials and Methods

The iron ore sample used in this research (50 kg) was sourced from Ajabanoko Mines, Kogi State, Nigeria, at Latitude and Longitude (WGS84): 7° 38' 20" North, 6° 20' 51" East. Two reference ores of granite (1 kg) and rutile (1 kg) were also sourced from the same location. The samples were further sampled, dried, geochemically and mineralogically characterised in preparation for liberation analysis.

2.1 | Geochemical and Mineralogical Characterisation of Ajabanoko Iron Ore

2.1.1 | XRF Analysis

The elemental composition of the samples was determined using an XRF analyser (S1 Titan 600N, Bruker AXS).

2.1.2 | XRD Analysis

The mineral phases present in the Ajabanoko iron ore were analysed using an XRD analyser (Bruker AXS D2 PHASER SSD16), and the acquired diffraction patterns were processed using the Diffrac Suite software to identify the different phases.

2.1.3 | SEM/EDS Analysis

The morphology of the test ore was determined using SEM (JEOL JSM-6510), while the elemental composition was confirmed by EDS analysis, integrated with EDAX APEX EDS for processing the photomicrographs and point analysis of the samples.

2.1.4 | Petrological Analysis

The Ajabanoko iron ore mineralogical textures and grain structure were assessed using thin sections inspected under a petrographic microscope (Leica Fein Optic EGB 100). This helped to distinguish various minerals based on color, evaluate the grain boundaries, and ore-mineral relationships.

2.1.5 | Particle Size Analysis, Distribution and Grindability Test

Particle size analysis of Ajabanoko iron ore was conducted to determine the particle size distribution, which is important for assessing mineral liberation. The samples (100 grams) were initially dried and pulverised to ensure uniformity and prevent moisture interference during sieving. A series of sieves with varying mesh sizes was used to classify the ore particles by size. The sieve sizes used followed a √2 progression and included +1200 µm, -1200+1000 µm, -1000+710 µm, -710+500 µm, -500+355 µm, -355+250 µm, -250+180 µm, -180+125 µm, -125+90 µm, and -90+63 µm sieves. The sieves were arranged on a sieve shaker, with the largest size (-1200+1000 µm) placed on top and the smallest sieve size (-90+63 µm) at the bottom, with a collection pan fitted below the bottom sieve to collect -63 µm particles. A lid was tightly placed on top of a -1200+1000 µm sieve to prevent any loss of particles during agitation, using standard procedures for mineral processing as described by Wills and Finch (2015)

Furthermore, two reference ores (overburden): granite and rutile, were prepared using the sieve analysis procedure, which served as control samples for grindability tests. 100 grams of both the Ajabanoko iron ore (test ore) and the reference materials (granite and rutile) were charged into a ball mill and ground for 15 minutes to ensure consistent grinding. The ground products were subjected to a sieve analysis using a mechanical sieve shaker for 30 minutes. The resulting products were weighed and recorded for particle size determination and grindability test using the Gaudin-Schumann equations (1-3).

$$P(X) = 100\,(X/K)\text{^}\alpha \quad (1)$$

$$\alpha = [\log P(X_2) - \log P(X_1)] / [\log X_2 - \log X_1] \quad (2)$$

Where P(X) is cumulative mass passing size, X is particle size (µm), K is size at 100% passing in the fitted distribution and α is distribution modulus or slope.

$$X_2 = X_1\,[P(X_2)/P(X_1)]\text{^}(1/\alpha) \quad (3)$$

For an 80% passing size the X_{80} is $X_1\,(80/P_1)\text{^}(1/\alpha)$

The work index was then calculated using the modified Bond's equation, which involves determining the energy input to the ball mill during grinding and the fineness of the ground material from sieve analysis data for the ore and the reference material. The work index was then calculated using the standard Bond equation, as shown in Equations 4 and 5.

$$E = W_i\,[10/\sqrt{P_{80}} - 10/\sqrt{F_{80}}] \quad (4)$$

Where E isspecific grinding energy (kWh/t); W_i is Bond Work Index (kWh/t); F_{80} is feed size at 80% passing (μm) and P_{80} is product size at 80% passing (μm).

$$W_{it} = W_{ir}\frac{\left[\frac{10}{\sqrt{P_r}} - \frac{10}{\sqrt{F_r}}\right]}{\left[\frac{10}{\sqrt{P_t}} - \frac{10}{\sqrt{F_t}}\right]} \quad (5)$$

Where W_{it} is the test ore Work Index, W_{ir} is the reference ore Work Index, P_r is the reference ore where 80% of the materials pass 100μm, P_t is the test ore diameter where 80% of the materials pass 100μm, F_r is the reference ore diameter where 80% of the feed pass 100μm, F_t is the test ore diameter where 80% of the feed pass 100μm, W_r is the reference ore work input and W_t is the test ore work input (Valerevich *et al.,* 2019).

3. | Results and Discussion

3.1 Geochemical and Mineralogical Characterisation

3.1.1 | XRF Analysis

The XRF results for the crude ore, as shown in Table 1, indicate that the iron ore is a low-grade sample, with 61.05% silica as the primary gangue, and an iron content of 34.28%, characteristic of low-grade ores. Other elements present in the ore were aluminium, phosphorus, calcium, and potassium, as well as traces of chromium, titanium, nickel, and zinc. Ore containing iron and high silica often results in challenges during beneficiation, as it is usually resistant to breakage; therefore, the energy required during grinding (Wills *et al.,* 2015).

The XRF results for the granite reference ore, shown in Table 2, show a very high silica content of 93.88%. This confirmed that the overburden mainly consisted of silica-rich material, which served as the main gangue in the ore.

The most abundant gangue in the rutile reference ore (Table 3) is titanium at 65.488% and silica with an assay of 11.777%. The reference ore's chemical analysis is relevant for understanding the gangue minerals associated with the Ajabanoko iron ore, which is crucial for effective beneficiation.

3.1.2 | XRD Analysis

The XRD micrograph of the crude ore shows distinct mineral phases at multiple 2θ angles, indicating the sample's crystalline nature (Figure 1). Key peaks are observed at 10.322°, 12.187°, 20.783°, 24.353°, 25.693°, 28.207°, 30.264°, and 31.122°. Quartz was the major phase, with visible hematite peaks, along with minor phases of saleeite and gunterite. Quartz, a silicate mineral, appears as a major phase, while hematite shows strong reflections, indicating that the main iron-bearing phase was hematite, with a silica

Table 1 | XRF Analysis of the Crude Ore

Elements	Si	Fe	Al	Ca	P	K	Cl	Mn	Ni	Pb	Cr	Ti
% Composition	61.05	34.28	2.68	0.87	0.32	0.31	0.19	0.08	0.05	0.04	0.03	0.03

Table 2 | XRF Analysis of Granite Reference Ore

Elements	Si	Al	Fe	K	Ca	P	Cl	Ti	S	Mn	Cu	Zr
% Composition	93.88	3.04	1.32	0.74	0.31	0.29	0.16	0.10	0.10	0.02	0.01	0.01

Table 3 | XRF Analysis of Rutile Reference Ore

Elements	Al	Ti	Mn	Fe	Zr	Nb	Si	Cl	K	Ca	Co	Zn
% Composition	2.69	65.49	0.48	17.94	0.03	0.38	11.78	0.02	0.21	0.36	0.38	0.05

gangue, a common feature of hematitic ores. The minor peaks observed are likely due to the presence of secondary minerals or trace impurities. The interconnection of quartz and hematite is common in many iron ores, such as banded formations, which often pose challenges during liberation due to strong mineral association (Gitau *et al.,* 2024).

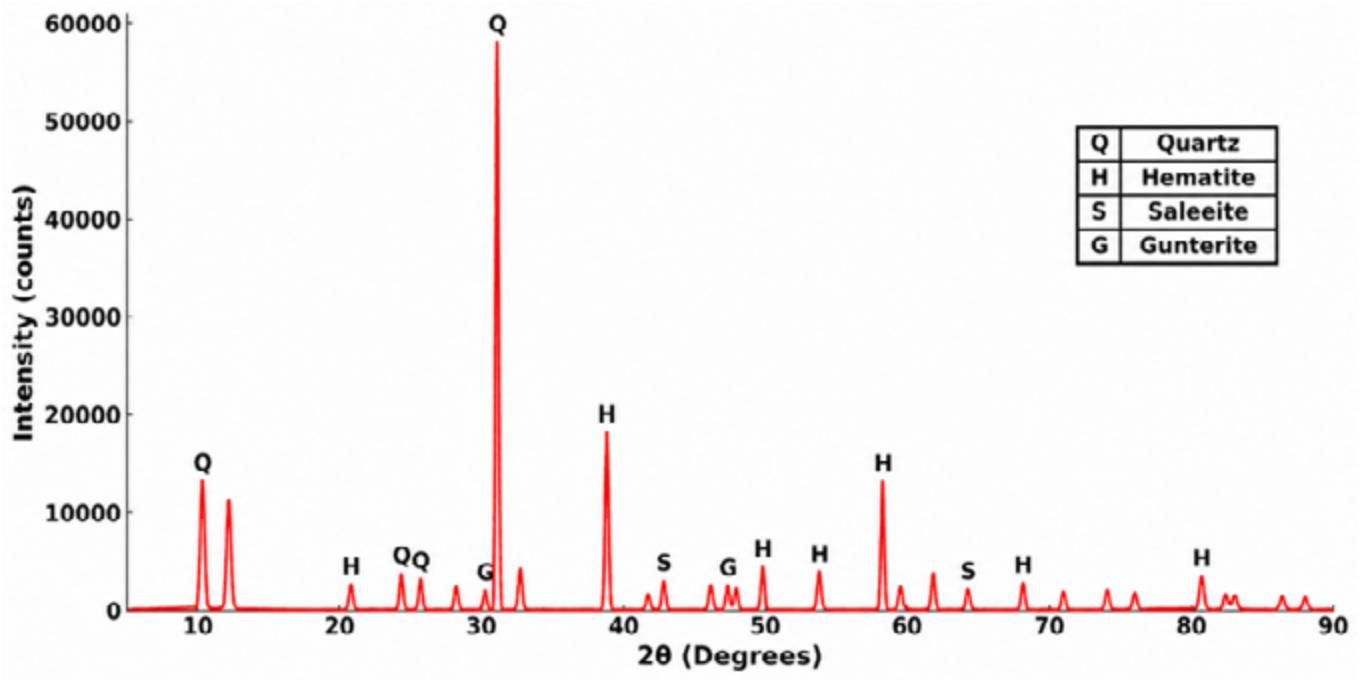


Figure 1 | XRD phase graph for crude Ajabanoko iron ore.

3.1.3 | Petrography Analysis

The sample is mostly translucent with light brownish to reddish colors, suggesting iron oxide staining. The minerals are visible and show a range of transparency and opacity, including quartz (translucent) and perhaps feldspar or iron oxides (reddish brown) as seen in Figure 2. The reddish regions observed could be due to hematite staining, a common occurrence in rocks with high iron content. There are also areas of strong interference colours, indicating the presence of minerals such as quartz and feldspar. Quartz is clearly visible in the larger grains. In both lighting conditions, the reddish, opaque areas remain visible, suggesting the presence of the mineral Fe_2O_3 (hematite). Alterations in minerals can be seen in the textural features of the ore; in this case, the ore grains are compacted and interlocking, which is directly related to the ore's grinding behavior; thus, it is necessary to determine it. Interlocked and compact mineral grains within the ore matrix always require more energy during grinding to achieve complete liberation (Lindsay *et al.,* 2016).

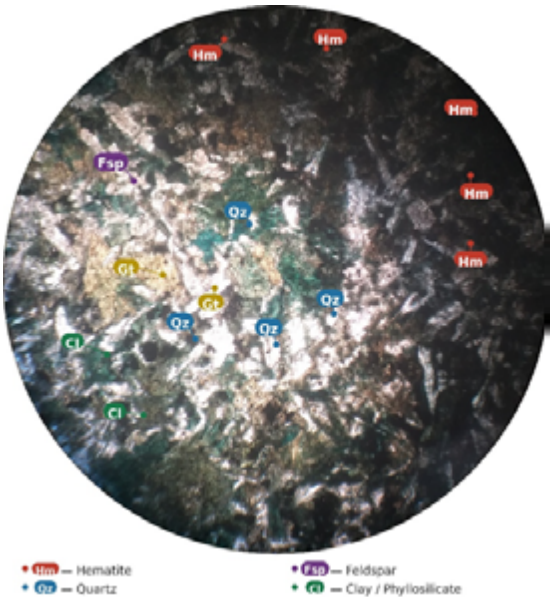
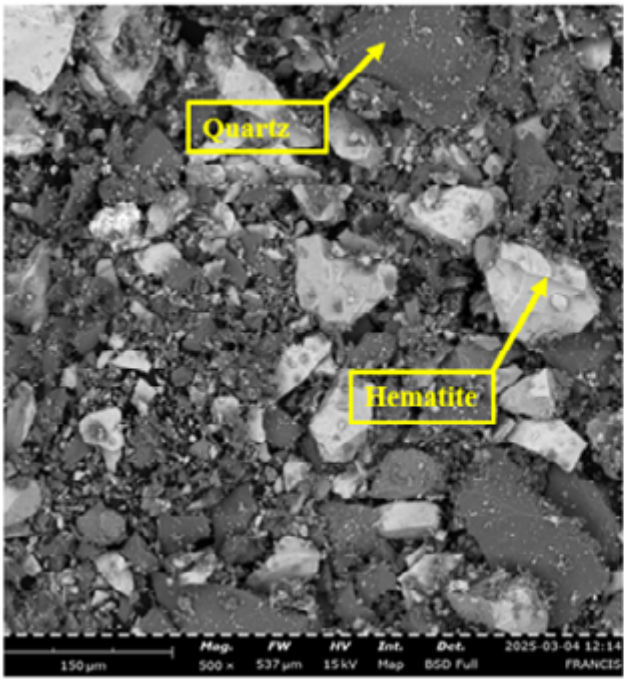


Figure 2 | Crude Ajabanoko iron ore sample under plane-polarised light (PPL)

3.1.4 | SEM-EDS Analysis

The SEM- EDS results (Figure 3) showed a complex mineralogy, with interlocked anhedral hematite on the pitted surface of subhedral quartz in the ore matrix. The analysis demonstrated that the sample contains well-defined hematite grains embedded in a silicate-rich gangue matrix. The interlocking compact grains in an ore are usually hard to separate, thereby affecting ore grinding, resulting in incomplete liberation and subsequent beneficiation. The EDS spot analysis of the sample, confirmed the elemental composition of high Fe (48.87%) and with silica (44.86%), confirming the presence of hematite and quartz as previously observed by SEM analysis with traces of Al, Ca, Mg, Ni, Mn, Ti, K, Na, indicating the presence of a more complex aluminosilicate, such as feldspar or clay minerals such as phyllosilicates.



Element Name	Element Symbol	Atomic Conc.
Iron	Fe	48.87
Silicon	Si	44.86
Aluminium	Al	2.87
Calcium	Ca	0.79
Magnesium	Mg	0.90
Nickel	Ni	0.36
Manganese	Mn	0.27
Titanium	Ti	0.20
Potassium	K	0.24
Sodium	Na	0.37
Vanadium	V	0.15
Chromium	Cr	0.12

Figure 3 | SEM-BSE micrograph and EDS elemental composition of Ajabanoko iron ore showing hematite (bright phases) and quartz (dark phases) as the dominant mineral constituents. EDS analysis confirms Fe and Si as the major elements, with atomic concentrations of 48.87% and 44.86%, respectively.

3.1.5 | Particle Size Analysis and Grindability Test

The sieve size analysis results are presented in the graph shown in Figure 4.

From the sieve analysis, the theoretical liberation size was determined to be -250+180 µm, the intercepting points on the sieve analysis graph in Figure 4. Liberation size determination is important as its gives information on how well the gangue and valuable minerals are separated, thereby providing insight into which sieve sizes to use during mineral beneficiation. Results from SEM-EDS and petrographic analysis indicated that hematite was not freely exposed but interlocked with quartz and other gangue in trace amounts. The results showed that at coarser particle sizes, hematite tends to remain locked together with quartz and other gangue minerals, as confirmed in the mineralogy assessment. This does not fully translate to full ore liberation, as complete liberation happens when the ore is finely ground to break up the bonding of hematite and silica, which should be confirmed by assaying at that exact sieve size. Gbadamosi *et al.* (2021) similarly reported

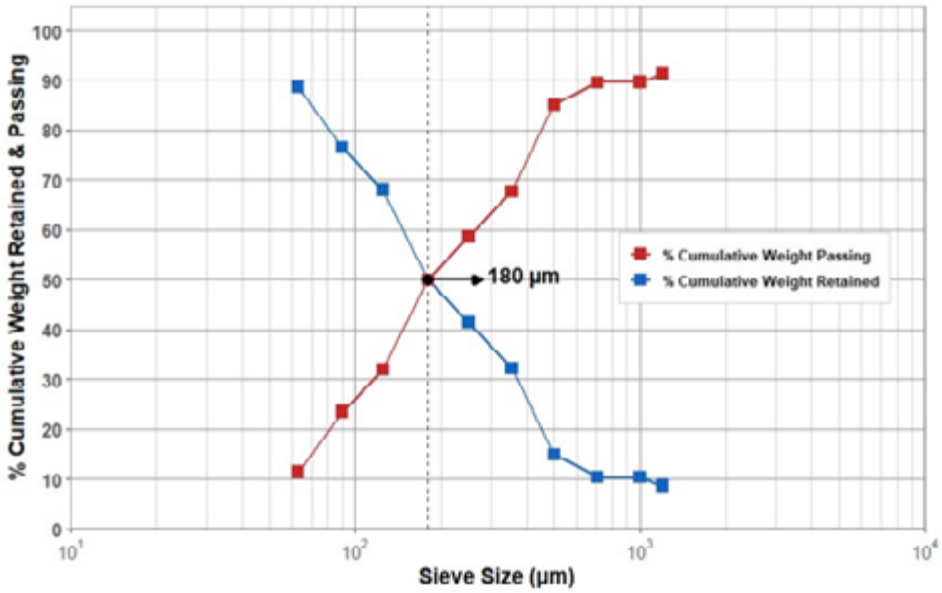


Figure 4 | Semi-log sieve size distribution curve showing cumulative weight retained and cumulative weight passing for the Ajabanoko iron ore sample.

that this form of behaviour occurs in complex ores containing mineral intergrowths and compact mineral grains, which makes it difficult to liberate.

Figures 5 and 6 present the outcomes of the sieve analysis of the test ore (Ajabanoko iron ore) and the two reference ores (granite and rutile). The findings were very important in establishing the WI and energy required to grind the Ajabanoko iron ore. Granite is known to have a work index of 15.13 kWh /t, and Rutile 12.68 kWh/t (Wills *et al.,* 2015). The work index and energy needed to grind the Ajabanoko ore to a liberation size were calculated using Equations 4 and 5, respectively, by replacing the particle size of the feed into and out of the ball mill for the reference (granite and rutile) and test ores.

$$Ft = X1\,\mu m = \left(\frac{\frac{80}{100}}{\frac{80.69}{100}}\right)^2 \times 1200 = 1179.65\,\mu m \text{ at } 80\%$$

$$Pt = X2\,\mu m = \left(\frac{\frac{80}{100}}{\frac{85.44}{100}}\right)^2 \times 180 = 157.80\,\mu m \text{ at } 80\%$$

$$Fr_1 = X3\,\mu m = \left(\frac{\frac{80}{100}}{\frac{71.45}{100}}\right)^2 \times 1200 = 1504.58\,\mu m \text{ at } 80\%$$

$$Pr_1 = X4\,\mu m = \left(\frac{\frac{80}{100}}{\frac{86.42}{100}}\right)^2 \times 180 = 154.25\,\mu m \text{ at } 80\%$$

$$Fr_2 = X5\,\mu m = \left(\frac{\frac{80}{100}}{\frac{70.89}{100}}\right)^2 \times 1200 = 1528.24\,\mu m \text{ at } 80\%$$

$$Pr_2 = X4\,\mu m = \left(\frac{\frac{80}{100}}{\frac{83.80}{100}}\right)^2 \times 180 = 163.74\,\mu m \text{ at } 80\%$$

The calculated Work Indices and energy required for the liberation of the Ajabanoko Iron Ore using Reference Ore 1 (Granite) are 16.40 kWh/t and 8.28 kWh, respectively. Two reference ores (granite and rutile) were used in determining the grindability of the Ajabanoko iron ore (test ore). The Work Index (WI) was calculated to be 16.40 kWh/t, and the amount of energy required to grind the test ore based on the granite reference ore was calculated to be 8.28

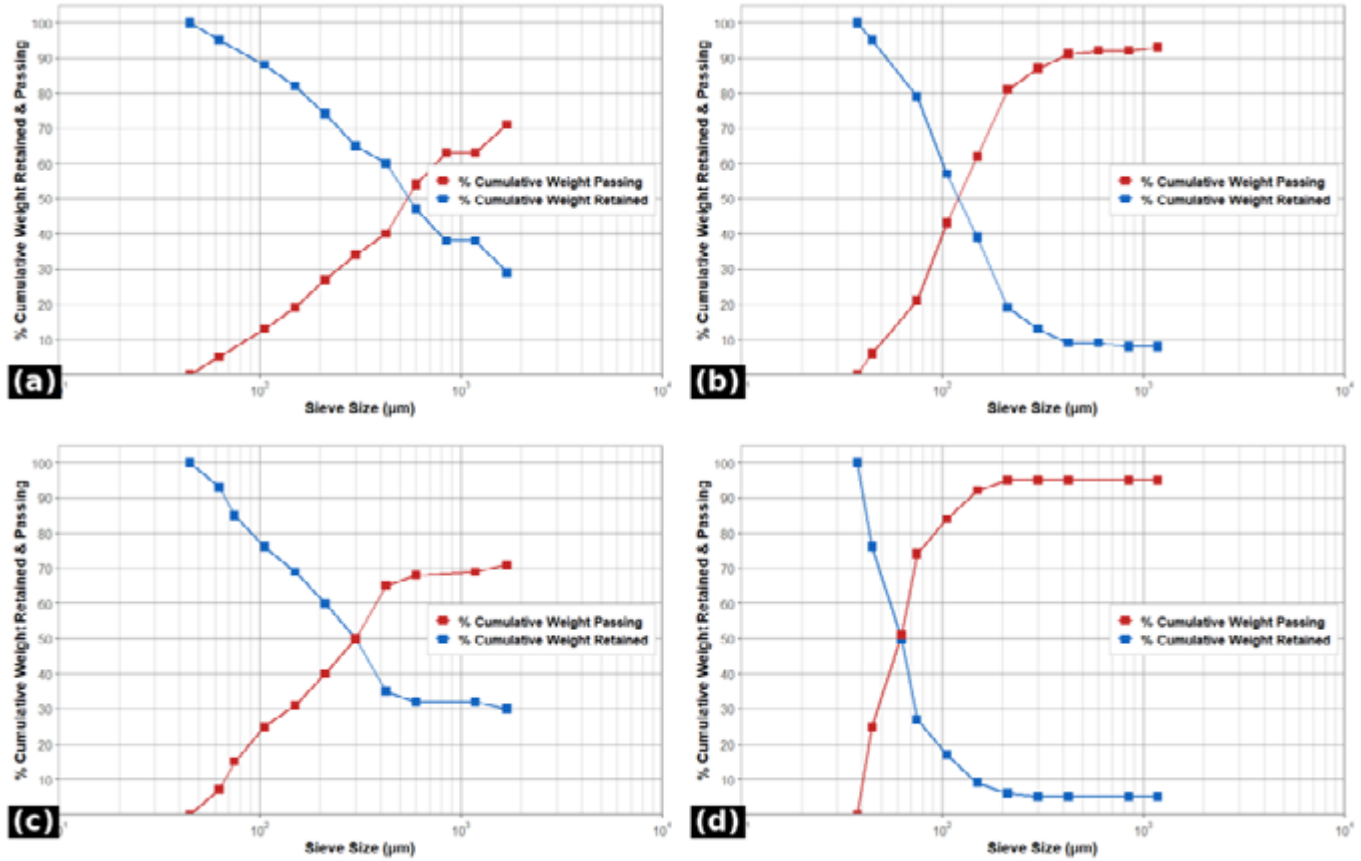


Figure 5 | Semi-log particle size distribution curves showing cumulative weight retained and cumulative weight passing for (a) granite reference ore feed to the ball mill, (b) granite reference ore product from the ball mill, (c) rutile reference ore feed to the ball mill, and (d) rutile reference ore product from the ball mill.

kWh. A lower WI of 13.20 kWh/t and energy of 6.67 kWh was obtained with rutile as the reference ore. Based on the results, the mean WI of 14.80 kWh/t for the Ajabanoko iron ore was determined, with an average energy of 7.47 kWh. The results indicate that the ore has moderate resistance to size reduction, while the differences between the two reference ores reflect their grinding properties. During comminution processes, a very small percentage of the energy provided is used to cause actual particle breakage. The majority of the energy is converted into heat, vibration, and noise, making ore grinding one of the least energy-efficient processes in mineral processing (Alabi *et al.,* 2016). The effectiveness of any mineral beneficiation method largely depends on selecting the most suitable separation method for the type of ore being processed, among other factors. This makes the mineralogical study of an ore a significant step in the development of the process, with awareness of the composition, texture, and distribution of minerals to determine liberation during grinding. Similar studies on ore grindability done by Alabi *et al.* (2016) reported that liberation is necessary, as it determines the extent to which the iron-bearing minerals can be separated from the silicate gangue encountered later in the beneficiation process.

The grindability test results of the Ajabanoko iron ore revealed that it is grindable in most conventional grinding circuits, as it is a moderately hard ore. However, the energy efficiency of the comminution process needs to be optimised as the ore has a complex mineralogy. These results are in agreement with the concepts of mineral processing outlined by Wills *et al.* (2015), which emphasize that

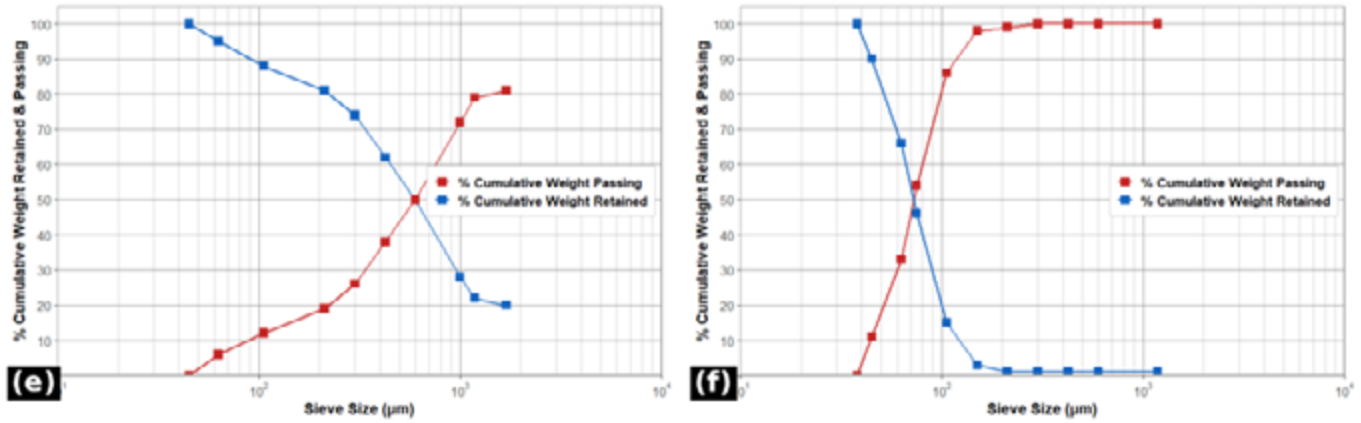


Figure 6 | Semi-log particle size distribution curves showing cumulative weight retained and cumulative weight passing versus sieve size for (e) Ajabanoko iron ore feed to the ball mill and (f) Ajabanoko iron ore product from the ball mill.

comminution effects and performance cannot be completely understood without taking into account the geochemical and mineralogical characteristics of the ore

4. | Conclusion and Recommendations

This study revealed that the mineralogical and textural characteristics of the Ajabanoko iron ore strongly affect the comminution process, which may have consequences in the later beneficiation stages. The Ajabanoko iron ore is silica-rich, with a dominant quartz phase and hematite as the primary iron-bearing mineral, confirming its low-grade nature. SEM-EDS micrographs and petrographic analysis show significant interlocking between iron minerals and quartz, which explains the challenges during liberation and the need for finer grinding. Although the theoretical liberation size was at -250 +180 µm, the high iron grades were reported in larger sieve sizes, highlighting the influence of mineral texture on grade distribution. The average Bond Work Index of 14.80 kWh/t shows a moderate value associated with the higher amount of hard quartz and complex mineral associations in the mineral matrix, which increases the energy required to reduce particle size further. The results obtained align with existing research, which emphasised the importance of the mineralogy on comminution performance (Wills *et al.,* 2015). The mineralogy and sieve-size analysis showed that there is a need to optimise the grinding conditions for the Ajabanoko iron ore to achieve adequate liberation of the ore without producing too much of the ultrafines that may reduce the efficiency of the beneficiation process. This would mean a progressive grinding at a controlled rate, and release the minerals in stages, with minimum energy usage.

There is a need for further studies with an emphasis on developing appropriate beneficiation methods for the ore as a function of the results of mineralogy and ore grindability optimisation. Besides, the use of advanced techniques for ore liberation analysis and investigation of new energy-efficient ways for comminution may enhance the general efficiency of the beneficiation operation. The mineralogical knowledge, coupled with the process optimization, is important in the utilization of Ajabanoko iron ore efficiently.

Acknowledgement

The authors wish to thank the Mineral Processing Laboratory of the Department of Metallurgical and Materials Engineering, Federal University of Technology, Akure, for allowing the use of its facilities during this research..

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