MINERAL ENGINEERING

Determination of Grindability Characteristics of Ovbiomu (Nigeria) Coal Towards Effective Beneficiation Process

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Abstract

The grindability of Ovbiomu coal (Nigeria) was determined using the Bond work index method. The investigation was carried out using a sourced coal sample as test ore from Ovbiomu village in the Owan East Local Government Area of Edo State, Nigeria. One reference ore (sandstone) was used, and it was found as an overburden of the coal deposit. Test ore was subjected to elemental characterization using an Ultimate analyzer while reference ore was subjected to chemical characterization using an energy-dispersive X-ray fluorescence spectrometer for their composition verification. These samples were crushed and ground under the same condition to give 100% passing through 1180 µm to obtain feed to the ball mill and product from the ball mill respectively. 100 gram of these were charged into an array of sieves set on root 2 ($\sqrt{2}$), that is, from 1000 to 63 µm, placed on a mechanical sieve shaker and shocked for 15 minutes, after which each sieve's content was weighed and recorded as weight retained. Data obtained were used to calculate % cumulative weight passing and retained and plotted against sieve sizes through which 80% passing was calculated using Gaudin Schumann's expression; the work index of sandstone as reference ore was calculated to be 18.4 kWh/t, and the work index of Ovbiomu coal was calculated to be 13.414 kWh/ton. While actual energy used in grinding Ovbiomu coal to its liberation size was calculated to be 2.10 kWh.

Keywords: grindability; beneficiation; sieve shaker; comminution; liberation size; particle size; work index

1 Introduction

Comminution processing is vital to the mineral processing industry because it involves reducing the size of mineral particles to enhance the effective separation of precious minerals from their associated minerals. Crushing and grinding are the two major stages of comminution [1]. Crushing process is the first stage of comminution, where various equipment, such as roll crushers, jaw crushers, and cone crushers, are used for primary, secondary, and tertiary crushing, while equiptments like rod mills, ball mills, autogenous mill, and semi-autogenous mill are used for grinding operation, which is the last stage of comminution operation after crushing [2].

Large amounts of energy are used during crushing and grinding operation [2]. Noise and heat, is one of the major problems owing to the fact that a large amount of the energy input is absorbed by the crushing and grinding equipment. As a result, breaking of the ore requires only a small portion of the energy input out of the large amount of energy used by the equipment[3].

According to research, the size reduction process only uses less than 1% of the total energy input, with the most energy being used to produce heat and noise [4] ; [5].

Bond work index (BWi) is one of the most important metric used in mineral comminution. It is calculated using Fred Bond's equation, which links energy used and reduction in particle size during the grinding operation [6]. The important equation used in this context is Bond's third law equation, which reveals the amount of energy used. However, the modified method of determining the work index of a mineral can be obtained using the Gaudin Schumann expression to determine the 80% passing size [2].

The comminution theories, such as Kicks, Rittingers, and Bonds have been used to establish the relationship between energy input and particle size reduction. According to these theories the material being ground is hard but brittle and that no energy is used throughout the comminution procedure that is not eventually used in ore breakup, none of these theories are sufficient in itself [3].

Importantly, note that, in the later process steps, every mineral have an ideal economical liberation particle size, known to as the liberation size. The recovery in the mineral separation procedures will be limited if the mineral or ore is reduced to a coarser particle size, this is because there won't be enough mineral liberated from their associate minerals. However, grinding the ore to a very fine particle size will result in higher energy consumption and grinding expenses and lower final recovery of the mineral if interest. By implication, effective mineral processing depends on efficient grinding operation [7].

Ovbiomu coal's grindability properties determination is essential for purpose of streamlining beneficiation process, which improve the coal's quality and value for industrial use. The possibility of grinding coal into smaller particles is called grindability, and it affects how much energy is used as well as how well later processing steps work [8]. Knowing these factors aids in choosing the right grinding equipment’s and settings, which will affects the overall profitability coal processing industry's [9].

Furthermore, because of their distinctive physical and chemical composition, different coal rank have variable grindability characteristics, that requires a specific beneficiation process [10]. Consequently, a proper grindability studies helps to increase effectiveness of the benficiation operation and promotes the sustainable use of coal as raw material in the energy industry [11].

Generally, the ability of coal to withstand crushing and grinding operations is determined by its grindability. This significantly impact combustion's cost and efficiency of the coal. The chemical characteristics and physical of coal are among the major factors that affect its grindability. To grind coal to a given particle size, the energy needed can be measured in terms of specific energy consumption, which is as a result of complicated interaction between material properties and mechanical forces. According to [12], a less energy is needed to grind the coal to the desired fine particle size, where larger values indicate easier grinding with less energy needed to grind coal. According to [13], this relationship can be established by the fact that the reduction in mineral particle size decreases the total resistance to grinding forces.

The Bond Work Index in this case, offers a standardized measure of grindability of the coal, for instance, studies show that the initial and final particle sizes can be connected to the energy needed for their grindability [6]. A lower value of Bond Work Index shows that the coal is easier to grind because less energy is required in this process [1]. while, coarser particle sizes are associated to higher energy values, suggesting a high resistance to grinding [14]

However, coal's grindability properties are significantly influenced by its mineral composition. Minerals deposits such as, quartz, clay and pyrite, are among the many inorganic and biological elements that form coal. The change in hardness and brittleness properties of some minerals can impact the ease of grinding. According to [15], the presence of hard minerals will result in higher milling energy consumption, while the presence of brittle minerals will make grinding operations easier. Therefore, predicting coal's streamlining milling and grindability operations will require an understanding of its mineral makeup.

A proper understanding of coal grindability characteristic is needed to optimize coal milling processes in industrial scale. Plan to reduce improve coal combustion efficiency and energy consumption can be developed by taking note factors such as, the moisture content, mineral composition and HGI, because it requires less energy to grind, coal with a high HGI value will be favoured when it comes to milling operations. Therefore, in order to reduce the energy needed for moisture content removal, coal with high moisture content may require pre-drying prior to milling operation [15].

It is important to remember that even though coal's grindability properties have been properly studied, the different types of coal ranks may cause discrepancies and uncertainties in the findings. To find the perfect milling conditions for a particular coal rank, the site study is necessary because different coal rank and sources can have different grindability properties [16].

For the minerals of interest to be separated effectively from the associate minerals in coal, as Ovbiomu coal, comminution (crushing and grinding) is required. Nevertheless, over-grinding and under-grinding are two important factors affecting comminution [12]. Therefore, in order to maximize the separation process and reduce losses, it is necessary to determine the energy needed for effective liberation. The type of comminution equipment and the process efficiency are also influenced by this determination. Given to these factors, this study uses the Bond work index to determine the grindability properties of Ovbiomu coal.

Finally, in the mineral processing industry, comminution processing which includes the crushing and grinding stages is fundamental for the separation precious minerals from associate minerals. Because grinding is the most energy-consumed process, the total amount of energy consume is a major concern. Energy absorption by the equipment’s themselves negatively affect the efficiency of comminution operations by producing noise and heat. Over- and under-grinding of coal can negatively affect the separation process and result in the loss of precious minerals. Therefore, it is important to determine the required energy needed for effective liberation and the Bond work index to is used determine the grindability characteristics for the purpose of optimization of the comminution process. In conclusion, particle size has a significant effect on the energy required to grind coal; higher energy values signifies simpler grinding operations [17].

1.1 Bond's work index determination

Gaudin Schumann's expression is majorly used to derive a modified approach for the determination of work index of Ovbiomu coal, which resulted in an 80% passing rate.

Gaudin Schumann's expression thus:

$$P(X) = 100\left(\frac{X}{K}\right)\alpha^{i} \tag{1}$$

Where:

P(X) = Cumulative percentage passing

x = Particle size

k = Size modulus

a = Distribution modulus

$$\alpha = \frac{LogP(x_2) - P(x_1)}{Log(x_2) - \mathrm{PLog}(x_1)} \quad (2)$$

$$\alpha = x_2 = \frac{\left(Px_2\right)^2}{\left(Px_1\right)^2} \times x_1 \quad (3)$$

Where:

$P(x_2)$ = Percentage Passing Size at 80 % passing.

$P(x_1)$ = Percentage Passing Size before 80 % passing

x_1 = Sieve size before 80 % passing

α = (x_2) = Sieve sizes at 80 % passing.

Using reference ore to calculate the work index of test ore, then we have

Energy used in Comminution (WGA) $= Wir\left(\frac{\frac{10}{\sqrt{Prs}} - \frac{10}{\sqrt{Frs}}}{\frac{10}{\sqrt{Pt}} - \frac{10}{\sqrt{Ft}}}\right)$ (4)

Where:

Wir = Work index of reference ore/mineral

Ft = Sieve size of Coal feed into ball mill, 80% passing through 100 µm

Pt = Sieve size of coal Product from the ball mill, 80% passing through 100 µm

Frs = Sieve size of Reference ore feed into ball mill, 80% passing through 100 µm

Prs= Sieve size of Reference ore Product from ball mill, 80% passing through 100 µm

Wit $= Wi\left(\frac{10}{\sqrt{Pt}} - \frac{10}{\sqrt{Ft}}\right)$ (5)

Where:

Wi = work index of the material comminuted. It is a relative measure of the resistance of the material to fracture. Ft, Pt = feed and product 80% passing size in microns Wit = energy required, kWh [2].

2 Material and method

2.1 Materials

Materials used for this research are coal samples sourced from Ovbiomu town in Edo State, Nigeria, while the one reference mineral was found from the test ore overburden in the same site at Owan East Local Government Council.

2.2 Methods

Fifty (50) kilograms of the coal sample were collected from five (5) different pits at the Ovbiomu coal opencast project located in Owan East Local Government with coordinates 7.0604°N, 6.0534°E in Edo State, Nigeria. These samples were collected at a dimension of 5 meters in length by 5 meters in breath by 12 meters in depth and with a distance of 100 meters apart. The sourced samples were mixed thoroughly and homogenized to obtain a uniform sample using the cone and quartering method of sampling. The grab sampling method was used to collect ten (10) kilograms of sandstone from each pit's overburden.

The lumpy coal was crushed using a Yu Feng 100 x 60 jaw crusher (model XL1349) and then ground using a ball mill (locally fabricated at Auchi Polytechnic) to a sieve aperture of 1180 μm until 100% passing was obtained. Five hundred (500) grams of the ground coal were collected using Jones Riffle's random sampling methods and prepared for chemical characterization to determine their elemental compositions. Hundred (100) grams of the ground coal was charged into an array of sieves arranged in root two ($\sqrt{2}$) (that is, from 1000 to 63 μm) on a Jinling Ro–Tap automated sieve shaker machine (model 890212050023) and shook for 15 minutes, after which the retained on each sieve was weighed and recorded as feed into a ball mill (Ft). A sample from this prepared sample was equally charged into a ball mill and ground for 20 minutes to a obtain ball mill product from further size reduction. 100 grams of this ball mill product were equally charged into a set of sieves. Retained products on each sieve were weighed and recorded. From the table, a log-log graph was used to plot the percentage of cumulative weight retained and passing against the sieve sizes in micrometers. These procedures were repeated for the reference mineral (sandstone).

2.3 Elemental characterization

2.3.1 X-ray fluorescence

X-ray fluorescence spectrometer operations, Sample preparation: For non-homogeneous samples, the sample was pulverized to a fine homogenous size 250 μm and then pelletized. Start sample testing, initialization (calibration), using a pure silver standard, select the working curve according to the test sample, output to Excel, and end.

2.3.2 Ultimate analysis

For this analysis, 200 – 250 mesh sieves were used to filter fifty (50) grams of the coal sample that had been finely ground. The Angstrom advance ultimate analyzer (model ADX-2500) was turned on and allowed to warm up for two hours. Finally, using pertinent programs, the coal sample was combusted in an ultimate analyzer, which measured the weight percent of hydrogen, nitrogen, oxygen, sulfur and carbon of the coal sample.

3 Results

Table 1. Summary of EDX chemical and ultimate analysis of the Ovbiomu coal deposit

Elements	Symbols	Composition (wt. %)
Carbon	C	27.68
Oxygen	O	29.56
Nitrogen	N	1.15

Elements	Symbols	Composition (wt. %)
Hydrogen	H	4.80
Sulphur	S	0.13
Aluminium	Al	0.89
Silicon	Si	6.82
Calcium	Ca	0.09
Titanium	Ti	0.10
Iron	Fe	0.53

Table 2. EDX chemical analysis of the Ovbiomu sandstone using ED-XRF

Compound	SiO_2	Al_2O_3	Fe_2O_3	Na_2O	K_2O	TiO_2	MnO	MgO	CaO	P_2O_5
Composition (wt. %)	77.12	12.07	2.68	1.67	2.44	0.83	0.79	0.81	0.76	0.83

3.1 Results of sieve analysis of the Ovbiomu crude coal

3.1.1 Results of sieve size analysis of the Ovbiomu coal (test feed) to the ball mill

Table 3. Result of sieve size analysis of the Ovbiomu coal (test feed) to the ball mill

Sieve size (µm)	Sieve size range (µm)	Weight retained (g)	% weight retained retained	Cumulative weight retained (%)	Cumulative Weight passing (%)
1000	1000	1.45	1.48	1.48	98.52
-1000+710	710	1.86	1.89	3.37	96.63
-710 + 500	500	3.73	3.80	7.17	92.83
-500 +355	355	3.54	3.60	10.77	89.23
-355+ 250	250	14.61	14.87	25.64	74.36
-250 + 180	180	48.28	49.14	74.78	25.22
-180 + 125	125	0.15	0.15	74.93	25.07
-125 + 90	90	0.17	0.17	75.10	24.90
-90 +63	63	0.20	0.20	75.30	24.70
-63	Pan	24.26	24.70	100.00	0.00
Total		98.25			

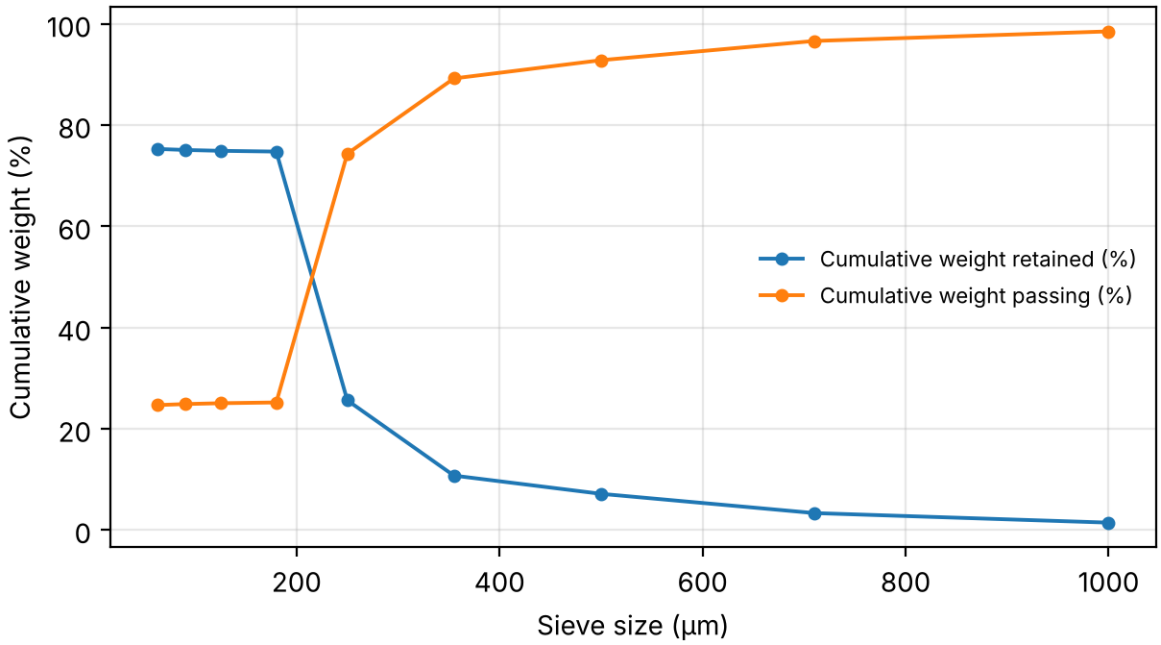


Figure 1. Cumulative weight retained (%) and cumulative weight passing (%) against sieve size (µm) of the Ovbiomu coal feed to the ball mill

Therefore, from Table 3 and Figure 1, to obtain 80% passing, the sieve size will be calculated using the Gaudin Schumann expression in Equation (3)

$$\alpha = x_2 = \frac{\left(Px_2\right)^2}{\left(Px_1\right)^2} \times x_1$$

$$X\mu m = Ft = \left(\frac{\frac{80}{100}}{\frac{Fr}{100}}\right)^2 \times x_1$$

$$X\mu m = \left(\frac{\frac{80}{100}}{\frac{74.36}{100}}\right)^2 = 250 \times = \left(\frac{0.8000}{0.7436}\right)^2 \times 250 =$$

$$(1.0726)^2 \times 250 = 1.1505 \times 250 = 287.63 \mu m$$

Test feed of coal (Ft) = 287.63 µm at 80%.

3.1.2 Sieve size analysis of the Ovbiomu coal (test product) from the ball mill

Table 4. Result of sieve size analysis of Ovbiomu coal (test product) from the ball mill

Sieve size (µm)	Sieve size range (µm)	Weight retained (g)	% weight retained retained	Cumulative weight retained (%)	Cumulative Weight passing (%)
1000	1000	0.73	0.74	0.75	99.25
-1000+710	710	0.13	0.13	0.88	99.12
-710 + 500	500	0.16	0.16	1.04	98.96
-500 +355	355	0.32	0.32	1.36	98.64

Sieve size (µm)	Sieve size range (µm)	Weight retained (g)	% weight retained retained	Cumulative weight retained (%)	Cumulative Weight passing (%)
-355+ 250	250	4.17	4.22	5.58	94.42
-250 + 180	180	79.16	80.09	85.67	14.33
-180 + 125	125	0.30	0.30	85.97	14.03
-125 + 90	90	0.20	0.20	86.17	13.83
-90 +63	63	0.15	0.15	86.32	13.68
-63	Pan	13.52	13.68	100.00	0.00
Total		98.84			

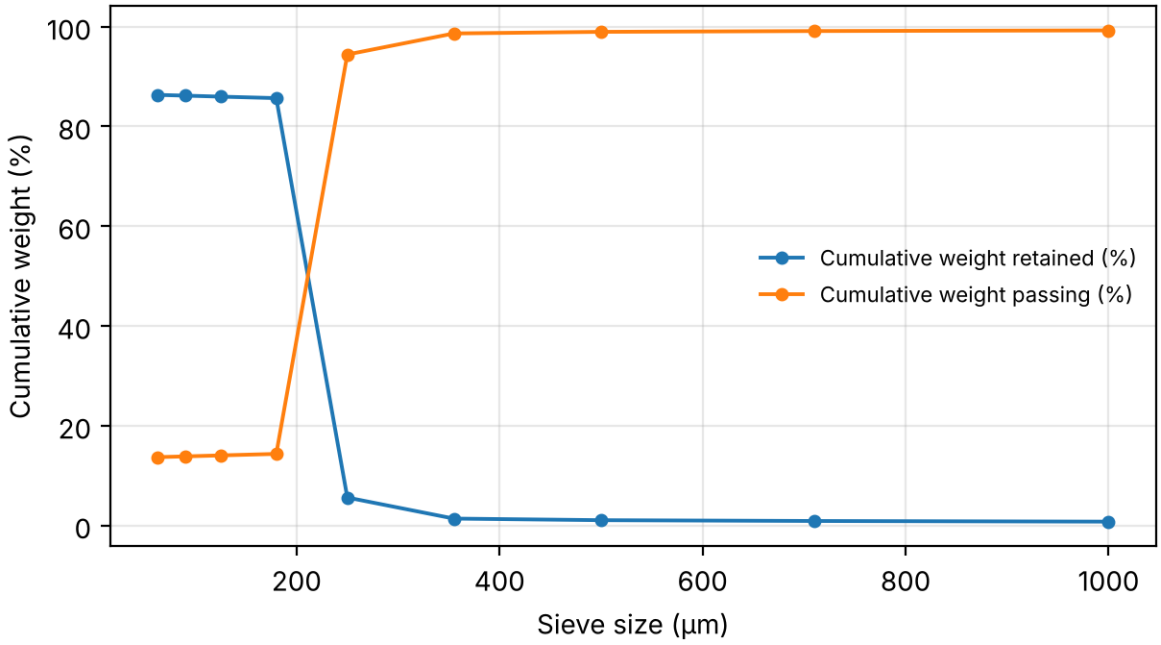


Figure 2. Cumulative weight retained (%) and cumulative weight passing (%) against sieve size (µm) of Ovbiomu coal product from the ball mill

Therefore, from Table 4 and Figure 2, to obtain 80% passing, the sieve size will be calculated using the Gaudin Schumann expression in equation (3)

$$\alpha = x_2 = \frac{\left(Px_2\right)^2}{\left(Px_1\right)^2} \times x_1$$

$$X\mu m = Pt = \left(\frac{\frac{80}{100}}{\frac{Pr}{100}}\right)^2 \times x_1$$

$$X\mu m = \left(\frac{\frac{80}{100}}{\frac{94.42}{100}}\right)^2 \times 250 = \left(\frac{0.8000}{0.9442}\right)^2 \times 250 =$$

$$(0.8473)^2 \times 250 = 0.7179 \times 250 = 179.48\mu m$$

Test product (Pt) of the coal = 179.48 µm at 80%.

3.1.3 Sieve size analysis of the Ovbiomu sandstone as reference mineral (test feed) to the ball mill

Table 5. Result of sieve size analysis of the Ovbiomu sandstone as reference mineral (test feed) to the ball mill

Sieve size (µm)	Sieve size range (µm)	Weight retained (g)	% weight retained retained	Cumulative weight retained (%)	Cumulative weight passing (%)
1000	1000	0.00	0.00	0.00	100
-1000+710	710	0.11	0.11	0.11	99.89
-710 + 500	500	1.21	1.23	1.34	98.66
-500 +355	355	27.61	28.09	29.43	70.57
-355+ 250	250	34.27	34.87	64.30	35.70
-250 + 180	180	20.96	21.33	85.63	14.37
-180 + 125	125	7.63	7.76	93.39	6.61
-125 + 90	90	4.51	4.59	97.98	2.02
-90 +63	63	1.56	1.59	99.57	0.43
-63	Pan	0.42	0.43	100.00	0.00
Total		98.28			

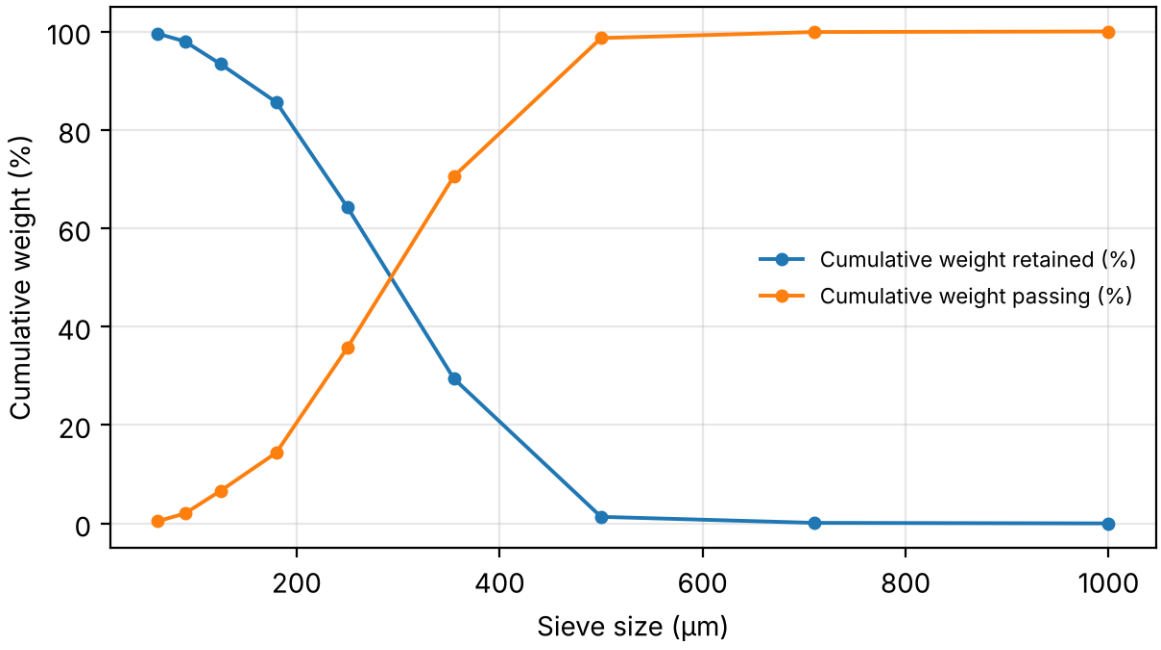


Figure 3. Cumulative weight retained (%) and cumulative weight passing (%) against sieve size (µm) of Ovbiomu sandstone (reference mineral) feed to the ball mill

Therefore, from Table 5 and Figure 3, to obtain 80% passing, the sieve size will be calculated using the Gaudin Schumann expression in Equation (3)

$$\alpha = x_2 = \frac{\left(Px_2\right)^2}{\left(Px_1\right)^2} \times x_1$$

$$\text{Xμm} = \text{Frs} = \left(\frac{\frac{80}{100}}{\frac{\text{Frs}}{100}}\right)^2 \times x_1$$

$$\text{Xμm} = \left(\frac{\frac{80}{100}}{\frac{70.57}{100}}\right)^2 \times 355 = \left(\frac{0.8000}{0.7057}\right)^2 \times 355 =$$

$$(1.1336)^2 \times 355 = 1.2850 \times 355 = 456.18\mu m$$

Test feed of sandstone (Frs) = 456.18 μm at 80%.

3.1.4 Sieve size analysis of the Ovbiomu sandstone as reference mineral (test product) from the ball mill

Table 6. Result of sieve size analysis of the Ovbiomu sandstone as reference mineral (test product) from the ball mill

Sieve size (μm)	Sieve size range (μm)	Weight retained (g)	% weight retained retained	Cumulative weight retained (%)	Cumulative weight passing (%)
1000	1000	0.00	0.00	0.00	100
-1000+710	710	0.02	0.02	0.02	99.98
-710 + 500	500	0.22	0.22	0.24	98.76
-500 +355	355	12.51	12.66	12.90	87.10
-355+ 250	250	28.29	28.62	41.52	58.80
-250 + 180	180	34.37	34.78	76.30	23.70
-180 + 125	125	15.08	15.26	91.56	8.44
-125 + 90	90	5.28	5.34	96.90	3.10
-90 +63	63	1.19	1.20	98.10	1.90
-63	Pan	1.87	1.90	100.00	0.00
Total		98.83			

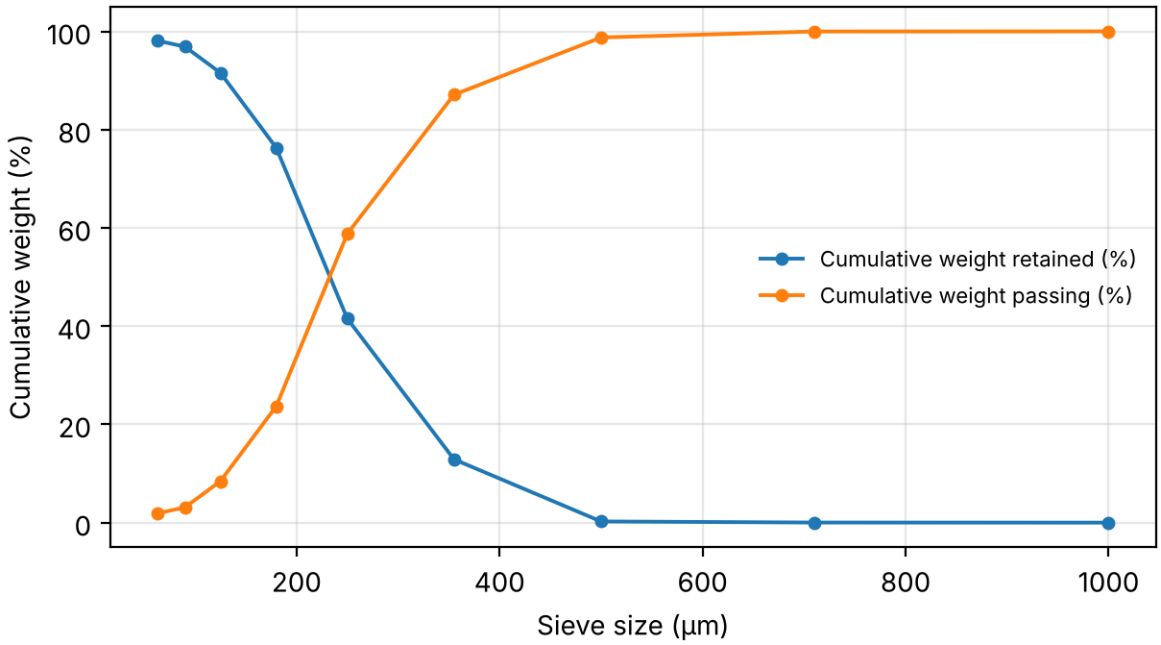


Figure 4. Cumulative weight retained (%) and cumulative weight passing (%) against sieve size (µm) of Ovbiomu sandstone product from the ball mill

Therefore, from Table 6 and Figure 4, to obtain 80% passing, the sieve size will be calculated using the Gaudin Schumann expression in Equation (3)

$$\alpha = x_2 = \frac{\left(Px_2\right)^2}{\left(Px_1\right)^2} \times x_1$$

$$\text{Xµm} = \text{Pts} = \left(\frac{\frac{80}{100}}{\frac{\text{Prs}}{100}}\right)^2 \times x_1 =$$

$$\text{Xµm} = \left(\frac{\frac{80}{100}}{\frac{87.10}{100}}\right)^2 \times 355 = \left(\frac{0.8000}{0.8710}\right)^2 \times 355 =$$

$(0.9185)^2 \times 355 = 0.8436 \times 355 = 299.48 \mu m$

Test product of sandstone (Prs) = 299.48 µm at 80%

Calculating the work index of Ovbiomu as test ore, using sandstone as a reference mineral using equation (4) Thus:

$$Wit = Wir\left(\frac{\frac{10}{\sqrt{Prs}} - \frac{10}{\sqrt{Frs}}}{\frac{10}{\sqrt{Pt}} - \frac{10}{\sqrt{Ft}}}\right)$$

Ft = 287.63 µm at 80% passing

Pt = 179.48 µm at 80% passing

Frs = 465.18 µm at 80% passing

Prs = 299.48 µm at 80% passing

Work index of Sandstone (Wrs) = 18.4 (Weiss, 1985)

$$\text{Work index of Ovbiomu coal (Wit)} = 18.4\left(\frac{\frac{10}{\sqrt{299.48}} - \frac{10}{\sqrt{465.18}}}{\frac{10}{\sqrt{178.48}} - \frac{10}{\sqrt{286.63}}}\right) =$$

$$\text{Wit} = 18.4 \times \left(\frac{\frac{10}{17.3055} - \frac{10}{21.5680}}{\frac{10}{13.3970} - \frac{10}{16.9597}}\right) =$$

$$\text{Wit} = 18.4 \times \left(\frac{0.5779 - 0.4636}{0.7464 - 0.5896}\right) =$$

$$\text{Wit} = 18.4 \times \left(\frac{0.1143}{0.1568}\right) =$$

$$18.4 \times 0.7290 = 13.414 KWh/t$$

Wit = 13.414 Kwh/t

Therefore, the energy required for comminution of Ovbiomu coal to its liberation size is, using equation (5)

$$\text{Et} = \text{Wit}\left(\frac{10}{\sqrt{\text{Pt}}} - \frac{10}{\sqrt{\text{Ft}}}\right) =$$

$$\text{Et} = 13.414\left(\frac{10}{\sqrt{179.48}} - \frac{10}{\sqrt{287.63}}\right) =$$

$$\text{Et} = 13.414\left(\frac{10}{13.370} - \frac{10}{16.9597}\right) =$$

$$\text{Et} = 13.414(0.7464 - 0.5896) =$$

$$\text{Et} = 13.414 \times 0.1568 = 2.1033 = 2.10\,\text{KWh}$$

Therefore, the required energy for comminution of Ovbiomu coal to its liberation size is 2.10 KWh.

4 Discussion

The EDX and ultimate analysis results are revealed in Table 1, which shows the weight percentage of carbon, nitrogen, hydrogen, sulfur, oxygen, aluminum, silicon, calcium, titanium, and iron, which amount to 71.75 weight percentage, while dirt, volatile matter, and ash containing other organic constituents account for 28.25 weight percentage of the coal deposit, as shown in Table 1, where the composition of nitrogen, hydrogen, oxygen, and sulfur are in agreement with[18].

Table 2 reveals that the selected overburden is primarily composed of 77.12% SiO_2, with major gangue as 12.07 % Al_2O_3, 2.68 % Fe_2O_3, and 2.44 % K_2O, along with a trace form of sodium oxide to the tune of 1.67 % Na_2O and other trace elements. Its relative characteristics as the test ore form the basis for its selection as a reference ore [19].

The results of fractional sieve analysis on the feed to the ball mill and product from the ball mill of Ovbiomu coal samples are shown in Figures 1 and 2, while Figures 3 and 4 show the graph of the particle size analysis of reference ore for 80% passing for both feed and product sieve size fractions for the test coal and reference ores (sandstone). A figure 1 and 2 show that 80% passing was obtained for 287.63 µm and 179.48 µm for the coal feed and product. 465.18 µm and 299.48 µm for sandstone as reference ore, from Figure 3 to obtain 80% passing, the test feed sieve size of sandstone (Frs) was calculated to be 456.18 µm using equation (3).

From Figure 4, to obtain 80% passing, the test product sieve size of sandstone (Prs) was calculated to be 299.48 µm using equation (3).

The work index (Wit) of Ovbiomu as test ore was calculated to be 13.414 kWh/t, with 18.4 kWh/t as the work index of sandstone as the reference mineral (Wrs) using equation (4), which is in line with the international acceptable standard [20]. This led to the calculation of the energy used in grinding Ovbiomu coal to its liberation size to be 2.10 kWh using Equation (5), out of which only one percent (1%) of the energy was used for the actual grinding and 99 % converted into other forms such as heat, noise and sound, which is in line with international acceptable standard [3].

These show that ball milling will effectively reduce the size of Ovbiomu coal particles, and processing Ovbiomu coal can be more cost-effective than the overburden sandstone. The value of the work index suggests advantageous features of the milling processes, which may result in lower operational costs and improved processing techniques.

Finally, the analysis offers important information on energy consumption and the milling efficiency and beneficiation of Ovbiomu coal to economic value can be achieved.

5 Conclusion

This research successfully determined the grindability characteristics of Ovbiomu low-grade coal and shows its suitability for an effective beneficiation process. The calculated work index of 13.414 kWh/ton proves that Ovbiomu coal possesses moderate resistance to grinding, making it compliant to conventional comminution techniques. More so, the energy needed to grind the Ovibiomu low-grade coal to its liberation size was determined to be 2.10 kWh, establishing that size reduction can be achieved with commensurate low energy input. These findings demonstrate that ball milling is an economically and efficiently viable method for grinding the Ovbiomu coal deposit.

From the technical results obtained, the importance of this study depends on its contribution to optimizing coal beneficiation processes in the nation. When compared to the associated overburden sandstone, the Ovbiomu coal has a relatively low energy requirement, which implies improved process efficiency and reduced operational costs. This improves the economic exploitation of the Ovbiomu coal and supports the improvement of the coal quality, such as its carbon content and calorific value of these locally available coal resources. By implication, the findings provide a scientific basis for designing energy-efficient and cost-effective coal beneficiation plants tailored to Ovbiomu low-grade coal characteristics.

Furthermore, the findings have significance for sustainable coal resource utilization. Efficient grinding operations will minimize processing waste and reduce unnecessary energy consumption, by implication supporting environmental friendly coal utilization practices. The increase in the calorific value also suggests an improved performance in industrial applications and combustion, which could strengthen the role of local and indigenous coal resources in Nigeria's energy mix.

For future study, researchers should focus on large-scale pilot testing to validate the laboratory findings under industrial conditions. Comprehensive studies on flotation performance, advanced beneficiation techniques, and mineral liberation analysis are also recommended to enhance product quality and recovery. For a broader framework for national coal beneficiation strategies, there should be comparative studies with other Nigerian coal deposits. Techno-economic analysis and environmental impact assessments should be done to make sure that using and improving Ovbiomu coal resources is both profitable and environmentally friendly.

Generally, this study provides important grindability data that not only improves the beneficiation possibilities of Ovbiomu coal but also supports deliberate development of Nigeria's solid mineral resources.

6 Recommendation

The Ovbiomu coal deposit should be ground as the energy consumption during this comminution operation will be economical; more than one concentration method should be used to beneficiate Ovbiomu coal to improve its calorific value and carbon content and ascertain if it can be used for domestic, metallurgical, and industrial purposes.

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Author contributions

All the authors contributed to formulating, developing, and drafting this research article.

Conflict of interest

The authors declare that there exist no known competing interests that could have appeared to influence the work reported in this paper.

References

[1] Wills BA, Napier-Munn TY. *Mineral processing technology: An introduction to the practical aspects of ore treatment and mineral recovery*. 7th ed. Elsevier; 2006. p. 108-115, 109-439.

[2] Alabi OO, Awogbamila OW. Determination of grindability characteristics of Duguri (Nigeria) galena towards effective beneficiation process. *Science and Technology*. 2020;6(22):83-92.

[3] Wills AB, Finch J. *Wills' mineral processing technology*. 8th ed. Butterworth-Heinemann; 2015. p. 212-234.

[4] Lynch AJ. *Comminution handbook*. Carlton (Victoria): Australasian Institute of Mining and Metallurgy; 2015. p. 43-49.

[5] Alabi OO, Yaro SA, Dungka GT, Asuke F, Dauda ET. Determination of work index of Gyel-Bukuru columbite ore, Plateau State, Nigeria. *Journal of Minerals and Materials Characterization and Engineering*. 2015;3(1):194-203.

[6] Bond FC. Crushing and grinding calculations. *British Chemical Engineering*. 1961;6(6):378-385.

[7] Onemine. *Summary and determination of Bond work index using an ordinary laboratory batch ball mill* [Internet]. 2010. http://www.onemine.org/serch//summary.emf

[8] Bhandari R, Sharma A, Gupta V. Grindability of coal: A review. *International Journal of Mining Science and Technology*. 2020;30(1):1-10.

[9] Kumar A, Singh R. Effects of coal properties on grindability. *Journal of Coal Science and Engineering*. 2019;27(4):389-397.

[10] Rao P, Gupta S. Characterization of coal for enhanced beneficiation. *Fuel Processing Technology*. 2021;211:106568.

[11] Sharma P, Verma A. Sustainable coal processing: An overview. *Resources, Conservation and Recycling*. 2022;179:106143.

[12] Berk D, Kocak M, Yilmaz M. An investigation of the grindability of coal. *Energy Sources, Part A: Recovery, Utilization and Environmental Effects*. 2019;41(1):1-10.

[13] Kahraman A. The effect of particle size distribution on the grindability of coal. *Minerals*. 2020;10(5):426.

[14] Ding Z, Zeng Y. Influence of coal particle size on the energy consumption in the grinding process. *Journal of Cleaner Production*. 2017;166:1328-1337.

[15] ASTM International. *Standard test method for grindability of coal by the Hardgrove machine*. ASTM D409-15. 2015.

[16] Smith J, Brown L. Variability in coal grindability: Implications for milling processes. *International Journal of Coal Science and Technology*. 2020;7(2):150-160.

[17] Mishra R, Kumar A. Energy requirements for fine grinding of coal: A review. *Energy Reviews*. 2021;2(1):45-60.

[18] Alabi OO, Adakole S, Osaghae OS. Assessment of Ovbiomu coal for industrial application. *Advanced Journal of Science, Technology and Engineering*. 2024;4(1):1-15.

[19] Hope GA, Woods R, Munce CG. Raman microprobe mineral identification. *Minerals Engineering*. 2001;14(12):1565-1577.

[20] Weiss NL. Particle characterization. In: *Mineral processing handbook*. American Institute of Mining and Metallurgical Engineers; 1985. vol. 1, p. 142-156.