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Determination of grindability characteristics of Duguri (Nigeria) galena towards effective beneficiation process

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ABSTRACT

The grindabiliy of Duguri (Nigeria) galena was determined using Bond work index method. The investigation was carried out using sourced galena (Lead ore) as test ore from Duguri village in Alkaleri Local Government area of Bauchi state, Nigeria. Two reference ores (Quartz and Granite) were used and were both found from the test ore's overburden. Both test ore and reference ores were subjected chemical characterization using Energy Dispersive X-ray fluorescence spectrometer for their composition verification. These samples were crushed and ground under same condition to give 100% passing through 1180μm to obtain feed to ball mill and product from ball mill respectively. 100g of these were charged into array of sieves set on root 2 (√2) i.e from 1000 to 63 μm placed on automotive sieve shaker and shock for 15 minutes after which each sieves content weighed and recorded. Data obtained were used to calculate % cumulative weight passing and retained and plotted against sieve sizes through which 80% passing was calculated using Gaudinshumma's expression to calculate work index of 20.58 Kwh/ton for quartz and 21.03 Kwh/ton for granite as reference ore respectively and the average of the two 20.805 Kwh/ton is recorded as the work index of Duguri galena. While actual energy used in grinding Duguri galena was calculated to be 11.77 KW.

Keywords: Grindability, Beneficiation, Sieve shaker, Comminution, Particle size.

1. INTRODUCTION

Mineral of interest is finely dispersed in its ore. Hence, comminution process precedes any mineral beneficiation process. The purpose of comminution in mineral processing is to prepare the ore as a suitable feed for further separation processes. Separation processing is to recover mineral of interest from its ore by rejecting the particle that do not contain economic amount of the target mineral (Lynch, 2015). The implication is that the comminution process changes the ore from a population of particles with relatively uniform grade to particle with a range of compositions that allow them to be separated into high grade and low grade streams. However, comminution theorem is interested in the relationship between the energy input in size reduction and the particle size made from a given feed size. Comminution theory expects that a relationship can be found between the energy required to break the material and the new surface created at the course of the comminution process. This relationship can only be made manifest if the energy used in the creation of new surface can be separately measured (Berry and Bruce, 1996). Many theories such as Kicks, Ritingers and Bonds have been presented, but none seems completely satisfactorily, for all the theories of comminution make the assumption that the materials is brittle and thus no energy is adsorbed in the comminution process which is not finally utilized in ore breakage (Wills and Finch, 2015). One must note that all ores have an economic optimum particle size (liberation size) in respect of following process stages. If the ore is ground to too coarse particle size, there will be insufficient mineral liberation limit recovery in the separation stage (Onemine, 2010). On the other hand, grinding the mineral to too fine particle size increases grinding cost, energy consumption and may reduce final recovery. Thus efficient grinding can be considered a key element to good mineral processing.

The stages of comminution processing are crushing and grinding (Wills and Napier, 2016). Crushing process which is the first stage in comminution process, consists of primary crushing, secondary crushing and tertiary crushing making use of Jaw crusher, cone crusher and roll crusher respectively. This will be followed by grinding which is the final stage in comminution process with the use of either Ball mill, rod mill, autogenous milling and/or semi - autogenous milling operation. In both Crushing and grinding process energy is expended (Bernhatdt, 1994). Grinding is the most energy intensive operation in mineral processing. Although to design and develop a crushing or grinding machine of high degree of mechanical efficiency and reliability, their energy efficiency is of great paramount (Norazirah *et al*. 2016). However, the greatest problem in all crushing and grinding machines is that the majority energy input is absorbed by the machine itself by converting into heat, noise production and a small fraction of energy input is available for breaking the ore. Wills and Finch (2015) established that less than 1% of the total energy input is available for actual size reduction process, the bulk of the energy being utilized in the production of heat and noise, while plastic material will consume energy while changing shape, but will then retain this shape without creating significant new surface (Lynch, 2015; Alabi *et a*l., 2015; Norazirah *et al*., 2016).

Ores like Duguri galena required comminution for effective liberation of the mineral of interest (s) from the associated compounds. However, the major detriments to comminution are under –grinding and over-grinding (Dessy, 2017). These problems pose adverse effect on the efficiency of the separation process and overall grade of ensuring concentrate. Appreciable amount of the mineral of interest are lost to tailing (Riantie *et al.,* 2013; Triantie and Wahyuni, 2013) which invariably leads to wastage in terms of energy, time, resources and effort. Hence, the need for evaluation of the actual amount of energy to be expended to effect efficient liberation is pertinent. This also influences the choice of comminution equipment and overall efficiency of the separation process. In lieu of this, this research to determine the grindability characteristics of Duguri galena using bond work index is a welcome development.

Bond work index determination

The modified method of determining the work index of Duguri galena involved the use of two reference ore of which work index was known. The procedure of determining 80 % passing was obtained using Gaudin Schumann expression thus:

$$P(X) = 100\left[\frac{X}{K}\right]^{\alpha} \quad i$$

$$\alpha = \frac{Log\, P(X2) - P(X1)}{Log(X2) - PLog(X1)} \quad ii$$

$$\alpha = Size_2 = \frac{(Percentage\ Passing\ Size_{2})^2}{(Percentage\ Passing\ Size_{1})^2} X\ Size_1 \quad iii$$

$$\text{Energy used in Comminution } (W_{GA}) = Wi\sqrt{\frac{10}{\sqrt{PG}} - \frac{10}{\sqrt{FG}}} \quad iv$$

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

$$Wit = W_{ir}\left[\frac{\frac{10}{\sqrt{Pr}}}{\frac{10}{\sqrt{Pt}}} - \frac{\frac{10}{\sqrt{fr}}}{\frac{10}{\sqrt{ft}}}\right] \quad v$$

Where:

F_{Ga} = Sieve size of Galena feed into ball mill, 80% passing through 100 μm
P_{Ga} = Sieve size of Galena Product from the ball mill, 80% passing through 100 μm
F_r = Sieve size of Reference ore feed into ball mill, 80% passing through 100 μm
P_r= Sieve sive of Reference ore Product from ball mill, 80% passing through 100 μm
F_t = Sieve size of Test ore feed into ball mill, 80% passing through 100 μm
P_t = Sieve size of Test ore Product from ball mill, 80% passing through 100 μm
W_r = Work input in kilowatt hour per ton for reference ore and
W_t= Work input in kilowatt hour per ton for test ore. (Alabi *et al,* 2016)

2. MATERIALS AND METHODS

Materials

Materials used for this research are Galena (Lead ore) sourced from Duguri town in Bauchi State Nigeria, while the two reference ore where found from the test ore over burden in the same site at Alkaleri Local Government Council.

Method

Twenty (20) Kilograms of Duguri galena was sourced from seven (7) different pits each on the mines site with each pit dug at a dimension of 4 meters length by 4 meters breath by 12 meters depth. This sourced samples were mixed together thoroughly homogenized to obtain a uniform sample using cut and quartering method of sampling followed by random sampling and Jones riffles sampling methods to arrive at the final 10 kg used for this research. This sampling method was used to collect ten (10) kilograms each of quartz and granite from each pit overburden. The grabbed ore samples were prepared for both Chemical Characterization to determine their elemental compositions and particle size analysis by crushing each to pass through 1180 μm sieve one after the other.

Crushing was done first by reducing the sizes of the galena (test ore) from boulders to 10 mm and charged into Denver laboratory jaw crusher (Model DXPC), followed by Denver cone crusher (Model DV 24355) and finally into the Endecott roll crusher (Model EQM -50 L) and unto sieve of aperture 1180 μm until 100% passing was obtained. This was repeated for both Test ore and the two reference ores. 100 grams of the ore was weighed using salter digital weighing balance and charged into array of sieves arranged in root two (√2) (i.e from 1000 – 63 μm) on an Endecott automated sieve shaker (Model d407) and shock for 15 minutes after which the retained on each saves were weighed and recorded (Feed into ball mill). Sample from this prepared sample was equally charged into Stretcher ball mill machine which contains 14 pieces of 10mm diameter steel balls, 18 pieces of 5mm steel ball making a total of 32 steel balls and were ground for 20 minutes to obtain ball mill product from further size reduction.100 grams of this ball mill product was equally charged into set of sieves as carried out the charge into ball mill. Retained on each sieves were weighed, recorded. The values obtained were plotted on a log – log graph after obtaining from the table of % weight comminution retained and passing against the sieve sizes in micro meter.

3. RESULTS AND DISCUSSION

Results obtained are stated on chemical analysis of the ores are presented on Tables 1 – 3 and that for the particle size is on Table 4 and Figures 1 – 6 respectively.

Chemical Analysis of Samples

Chemical composition of Duguri Galena ore and the reference ores (Quartz and Granite) are presented on Tables 1 – 3 respectively.

Table 1: Chemical Analysis of Galena ore using ED-XRF

Compound	SiO_2	K_2O	TiO	Fe_2O_3	CuO	ZnO	PdO	CdO	BaO	PbO
% Composition	20.0	1.1	0.42	1.95	0.664	22.38	1.2	2.7	0.37	48.2

Table 2: Chemical Analysis of Quartz (Reference ore) using ED-XRF

Compound	SiO_2	K_2O	CaO	TiO_2	Cr_2O_3	MnO	Fe_2O_3	PbO	RuO_2	Y_2O_3
% Composition	80.47	0.47	1.11	0.42	3.05	3.02	7.302	0.54	0.24	1.14

Table 1: Chemical Analysis of Granite (Reference ore) using ED-XRF

Compound	Al_2O_3	SiO_2	K_2O	CaO	TiO_2	MnO	Fe_2O_3	RuO_2	PbO	ZrO
% Composition	12.0	42.30	0.91	18.1	2.32	0.33	20.17	0.67	0.41	0.20

From Table 1, Duguri galena was found to contain predominantly lead oxide to the tune of 48.2 % PbO and other associated element such as 22.38 % ZnO, 20% SiO_2 and 1.95 % Fe_2O_3 alongside other trace compound. This result shows clearly that Galena is Lead ore with other impurities such as silica, iron oxide and Zinc ore as major impurities and potassium, copper, cadmium, barium and titanium as trace impurities. Duguri galena ore can be regarded as a high grade lead ore assaying 48.2 % PbO, hence it is economically viable to be explored and exploited for metallurgical purposes (Abraham *et al.,* 2012).

Table 2, shows that the overburden of the lead ore contains mostly silica oxide in quartz form to the tune of 80.47% SiO_2 with other minor and major gangues such as iron ore (7.302% Fe_2O_3), Cromiumoxide (3.05%Cr_2O_3) and manganese oxide (3.02 % MnO) with trace form of lead oxide of 0.54 % PbO which forms the basis for the choice of the reference ore used (Lucas *et al.,* 2014).

Table 3, shows that the chosen over burden contains predominantly 42.3 % SiO_2, with major gangue as 20.17 % Fe_2O_3, 18.1 % CaO and 12 % Al_2O_3 with trace form of lead oxide to the tune of 0.41%PbO, with other trace gangues; which makes it possess relative characteristics as the test ore, which forms basis for its choice as a reference ore (Naptier, 1996; Hope, *et al.,* 2001).

Particle Size Analysis

Table 4 and 5 shows the result of particle size distribution for feed (test ore) into ball mill and its product from ball mill respectively. While Figures 1 – 6 shows the log – log graph of % Cumulative retained and % cumulative weight passing against each sieve sizes in micro meter.

Table 4: Result of sieve size analysis of Galena (test feed) to ball mill

Sieve sizes (μm)	**Sieve size Range (μm)**	**Weight retained (g)**	**% weight Retained**	**Cumulative Weight Retained (%)**	**Cumulative Weight Passing (%)**
+ 1000	1000	2.50	2.56	2.56	97.44
-1000 + 710	710	8.70	8.92	11.48	88.52
-710 + 500	500	9.40	9.64	21.12	78.88
-500 + 355	355	9.90	10.15	31.27	68.73
-355 +250	250	10.90	11.19	42.46	57.54
-250 + 180	180	22.20	22.77	65.23	34.77
-180 + 125	125	21.70	22.26	87.49	12.51
-125 + 90	90	4.70	4.82	92.31	7.69
-90 + 63	63	4.70	4.82	97.13	2.87
-63	pan	2.80	2.87	100.0	0
		97.5			

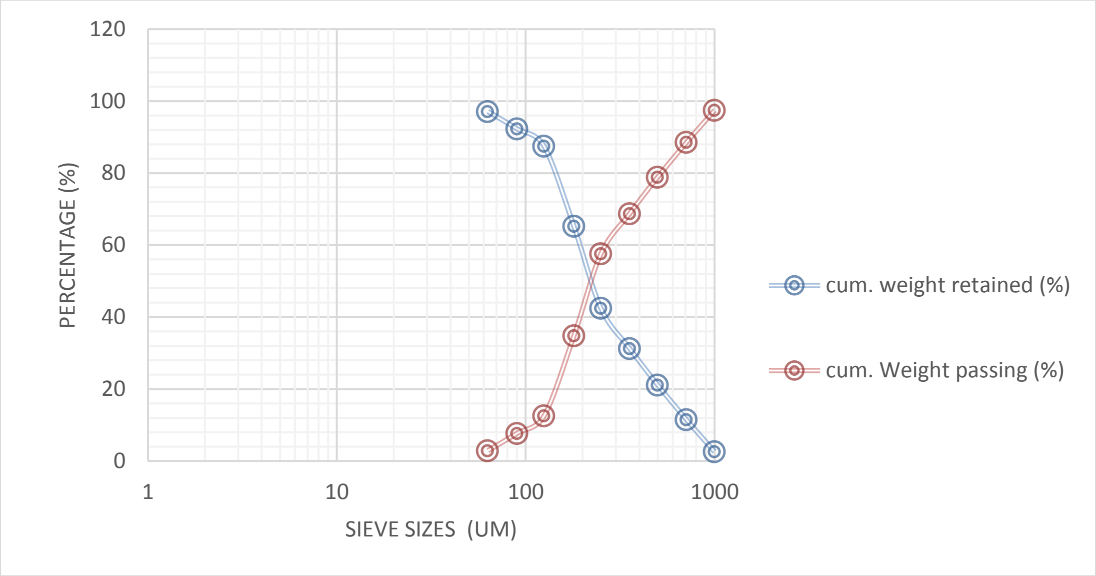

Figure 1: Shows % Cumulative weight Retained and % Cumulative weight passing against Sieve sizes (µm) of galena feed to the ball mill.

Therefore, From the Table 4 and Figure 1 to obtain 80% passing the sieve size will be calculated using Guadinshumann expression in equation iii

$$\alpha = \text{Size}_2 = \frac{(Percentage\ Passing\ Size_2)^2}{(Percentage\ Passing\ Size_1)^2} \text{ X Size}_1$$

$$X\mu m = F_t \left(\frac{\frac{80}{100}}{\frac{78.88}{100}}\right)^2 \text{ x } 500$$

F_t = 514.10 µm at 80%.

Table 5: Result of sieve size analysis of Galena (test product) from ball mill

Sieve sizes (µm)	Sieve size Range (µm)	Weight retained (g)	% weight Retained	Cumulative Weight Retained (%)	Cumulative Weight Passing (%)
+ 1000	1000	0.20	0.20	0.2	99.80
-1000 + 710	710	0.60	0.61	0.81	99.19
-710 + 500	500	0.40	0.41	1.22	98.78
-500 + 355	355	0.90	0.92	2.14	97.86
-355 +250	250	2.00	2.04	4.18	95.82
-250 + 180	180	36.40	37.02	41.20	58.80
-180 + 125	125	42.90	43.64	84.84	15.16
-125 + 90	90	5.50	5.60	90.44	9.56
-90 + 63	63	3.60	3.66	94.10	5.90
-63	pan	5.80	5.90	100.0	0.0
		98.0			

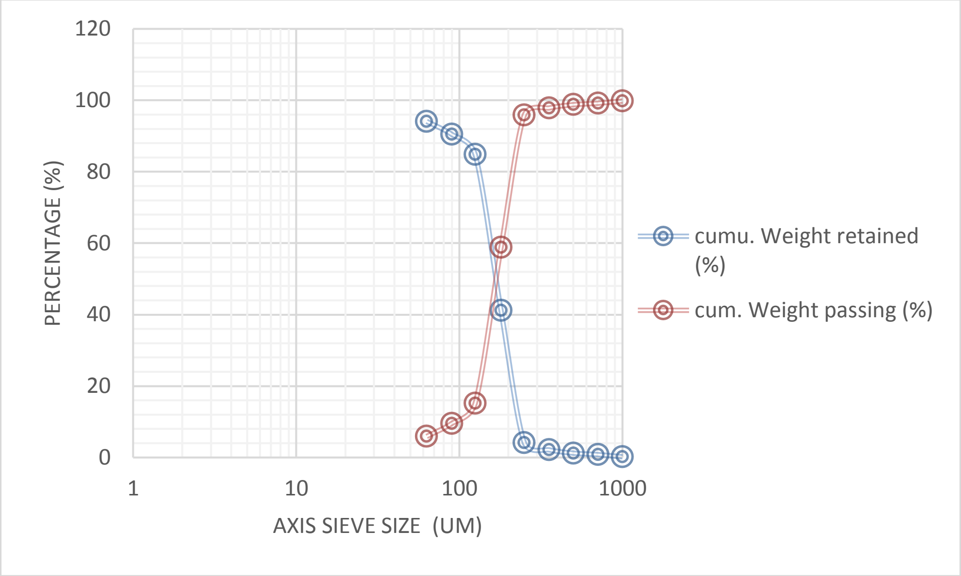

Figure 2: Shows % Cumulative weight Retained and % Cumulative weight passing against Sieve sizes (µm) of galena product from the ball mill.

Therefore, From the Table 5 and Figure 2 to obtain 80% passing the sieve size will be calculated using Guadinshumann expression in equation iii

$$\alpha = \text{Size}_2 = \frac{(Percentage\ Passing\ Size_{2)}2}{(Percentage\ Passing\ Size_{1\ )2}} \text{ x Size}_1$$

$$X\mu m = P_t = \left(\frac{\frac{80}{100}}{\frac{95.83}{100}}\right)^2 \text{ x } 250$$

$$P_t = 174.25\ \mu m \text{ at } 80\%.$$

For Quartz as a reference ore

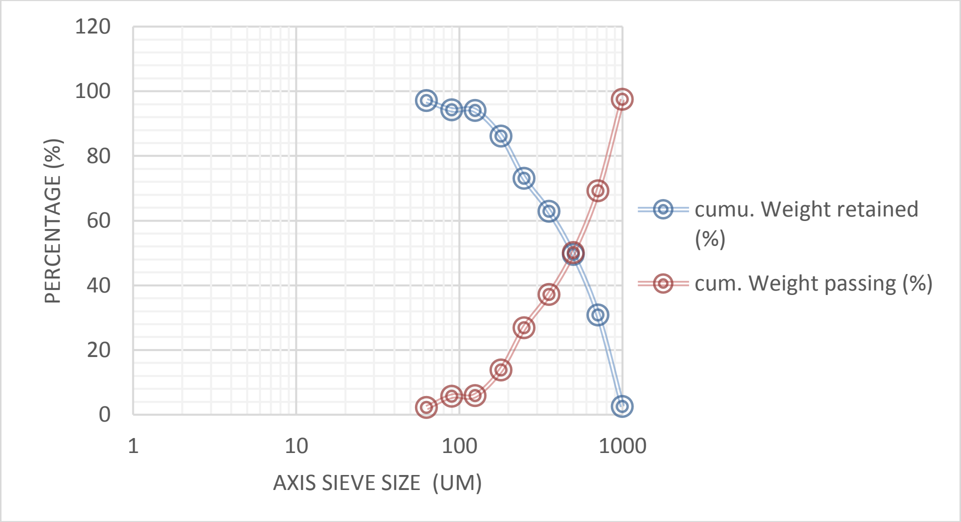

Figure 3: Shows % Cumulative weight Retained and % Cumulative weight passing against Sieve sizes (µm) of Quartz (reference ore) Feed into the ball mill.

Therefore, From Figure 3 to obtain 80% passing the sieve size will be calculated using Guadinshumann expression in equation iii

$$\alpha = Size_2 = \frac{(Percentage\ Passing\ Size_2)2}{(Percentage\ Passing\ Size_1)_2} \text{ X } Size_1$$

$$X\mu m = F_{rq} = \left(\frac{\frac{80}{100}}{\frac{69.22}{100}}\right)^2 \text{ x } 710$$

F_{rq} = 948.28 μm at 80%

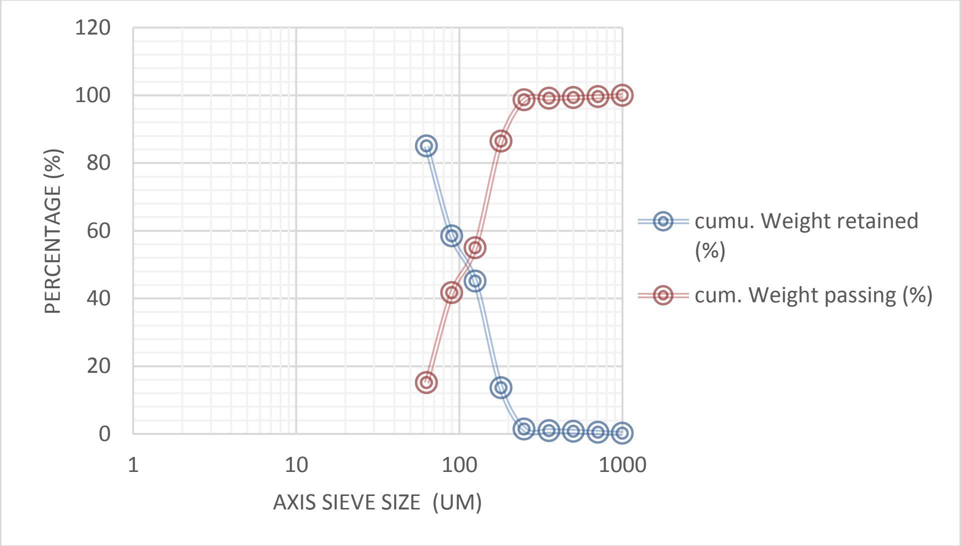

Figure 4: Shows % Cumulative weight Retained and % Cumulative weight passing against Sieve sizes (μm) of Quartz (reference ore) Product from the ball mill.

Therefore, From Figure 4 to obtain 80% passing the sieve size will be calculated using Guadinshumann expression in equation iii:

$$\alpha = Size_2 = \frac{(Percentage\ Passing\ Size_2)2}{(Percentage\ Passing\ Size_1)_2} \text{ X } Size_1$$

$$X\mu m = P_{rq} = \left(\frac{\frac{80}{100}}{\frac{86.42}{100}}\right)^2 \text{ x } 180$$

P_{rq} = 154.35 μm at 80%

For Granite as a reference ore

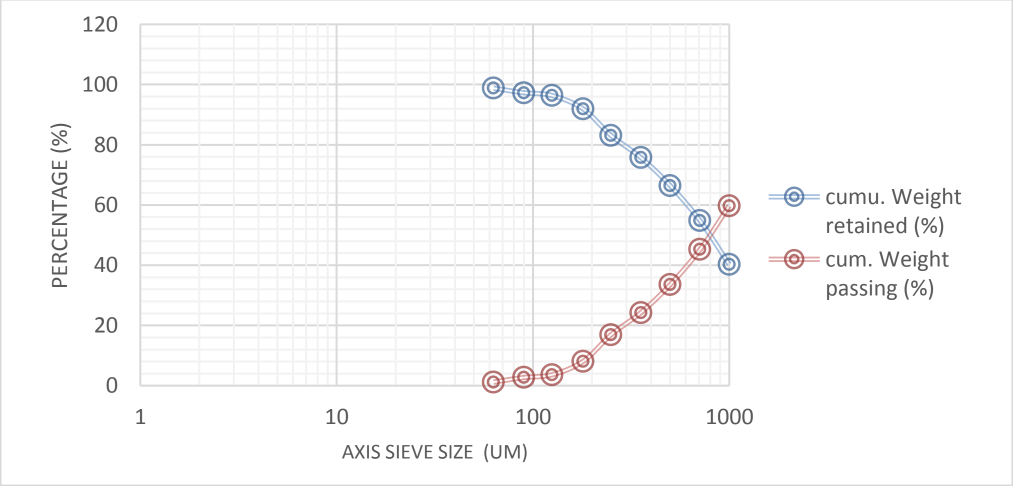

Figure 5: Shows % Cumulative weight Retained and % Cumulative weight passing against Sieve sizes (μm) of Granite (reference ore) Feed to the ball mill.

Therefore, From Figure 5 to obtain 80% passing the sieve size will be calculated using Guadinshumann expression in equation iii:

$$\alpha = \mathrm{Size}_2 = \frac{(Percentage\ Passing\ Size_{2})2}{(Percentage\ Passing\ Size_{1})_2}\ \mathrm{X\ Size}_1$$

$$\mathrm{X\mu m} = F_{rg} = \left(\frac{\frac{80}{100}}{\frac{59.72}{100}}\right)^2\ \mathrm{x}\ 1000$$

F_{rg}= 154.35 µm at 80%

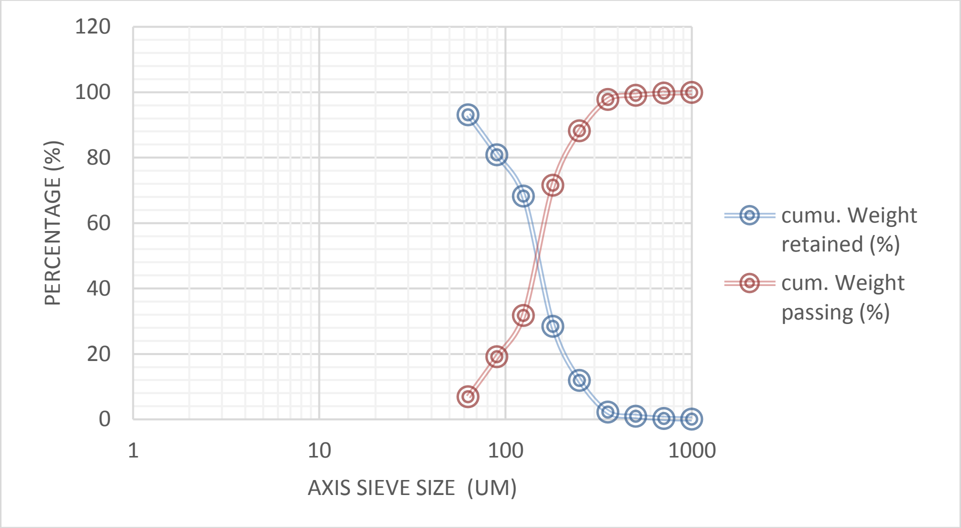

Figure 6: Shows % Cumulative weight Retained and % Cumulative weight passing against Sieve sizes (µm) of Granite (reference ore) Product from the ball mill.

Therefore, From Figure 6 to obtain 80% passing the sieve size will be calculated using Guadinshumann expression in equation iii:

$$\alpha = \mathrm{Size}_2 = \frac{(Percentage\ Passing\ Size_{2})2}{(Percentage\ Passing\ Size_{1})_2}\ \mathrm{X\ Size}_1$$

$$\mathrm{X\mu m} = P_{rg} = \left(\frac{\frac{80}{100}}{\frac{71.56}{100}}\right)^2\ \mathrm{x}\ 180$$

P_{rg}= 224.95 µm at 80%.

Calculating Work index of Duguri Galena as test ore, using Quartz as a reference oreusing equation v, Thus:

$$\mathrm{Wit} = W_{ir}\left[\frac{\frac{10}{\sqrt{Pr}}}{\frac{10}{\sqrt{Pt}}} - \frac{\frac{10}{\sqrt{fr}}}{\frac{10}{\sqrt{Ft}}}\right] \qquad \mathrm{v}$$

F_r = 514.10 µm at 80% passing
P_t = 174.25 µm at 80% passing
F_{rq}= 948.28 µm at 80% passing
P_{rq} = 154.35 µm at 80% passing

Work index of Quartz (Wrq) = 13.57 (Alabi, *et al.,* 2016)

Work index of Duguri Galena (Wit) = 13.57 $\left[\frac{\frac{10}{\sqrt{154.35}}}{\frac{10}{\sqrt{174.25}}} - \frac{\frac{10}{\sqrt{948.28}}}{\frac{10}{\sqrt{514.10}}}\right]$

= 20.58 KWh/t

Calculating Work index of Duguri Galena as test ore, using Granite as a reference ore using equation v, Thus:

F_r = 514.10 µm at 80% passing
P_t = 174.25 µm at 80% passing
F_{rg}= 1794.5 µm at 80% passing
P_{rg} = 224.95 µm at 80% passing

Work index of Granite (Wrg) = 15.13 KWh/ton (Onemine, 2010; Alabi, *et al.,* 2016)

Work index of Duguri Galena (Wit) = 15.13$\left[\frac{\frac{10}{\sqrt{224.95}}}{\frac{10}{\sqrt{174.25}}} - \frac{\frac{10}{\sqrt{1794.5}}}{\frac{10}{\sqrt{514.10}}}\right]$

= 21.03 KWh/t

Generally work index of Duguri galena will be the average of the two calculated work index gotten using the two reference ore:

= $\frac{20.58+21.03}{2}$ KWh/ton

= 20.805 KWh/ton

Energy used in comminution process of Duguri galena ore to its liberation size is found using the

Work Energy = W_t = Wi $\sqrt{\frac{10}{\sqrt{PG}} - \frac{10}{\sqrt{FG}}}$ iv

W_t = 20.805 $\sqrt{\frac{10}{\sqrt{174.25}} - \frac{10}{\sqrt{514.10}}}$

= 20.805 X $\sqrt{0.3166}$

= 20.805 X 0.5627

= 11.77 KW

From the results obtained having carried out fractional sieve analysis on the feed to ball mill and product from the ball mill of the ore samples contained in Tables 1 and 2. And Figures 1 – 6 show the plots of the particle size analysis of reference and test ores 80 % passing for both feed and product sieve size fractions for the test ore (Galena) and reference ores (Quartz and Granite). The results obtained from the experiment performed on Duguri lead ore, Bauchi state using modified Bond's energy method. Figures 1 and 2 show that 80% passing was obtained to be 514.10 µm and 174.25 µm for test ore at the feed and product. 948.28 µm and 154.35 µm for quartz as reference ore as in Figure 3 and 4 for feed and product respectively.1794.50 µm and 224.94 µm were also obtained when granite was used as reference ore as shown in Figures 5 and 6 respectively. However, from this values work index of Duguri Lead ore was calculated to be 20.58 Kwh/ton and 21.03 Kwh/ton using quartz and granite as reference ores respectively. Therefore, the actual Duguri Galena work index was calculated by finding the average of the two values to be 20.805 Kwh/ton, as is within the standard galena work index of 4.23 – 23.63 Kwh/ton (Alabi, *et al.,* 2016). This lead to the calculation of the energy used in grinding galena to its liberation size be 11.77 Kw out of which only one percent (1%) of the energy was used for the actual grinding and 99 % transmitted into other forms such as heat, noise and so on (Magdalimovic, 1989; Wills and Finch, 2015).

4. CONCLUSION

The grindability characteristics of Duguri galena was determine by characterization of the test and the reference ores, followed by the determination of its work index using Bonds method and calculation of the energy used in comminution this test ore to its liberation size for effective beneficiation towards value addition. It can then be concluded that:

i. Duguri Galena contains 48.2% PbO and other gangue as impurities and known to be lead ore. It can therefore be concluded to be a high grade lead oxide that needs further beneficiation to meet up the standard of 65%PbO needed as a charge for further extraction of lead metal for engineering purposes.
ii. Work index of Duguri galena was calculated to be 20.805 Kwh/ton on an average; and
iii. Energy used in grinding this ore to its liberation size was found out to be 11.77 Kwh/ton.
iv. Finally, these parameters are significant in the design of a comminution machine in process route for the beneficiation of Duguri galena (lead ore) which contains Lead oxide.

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Conflict of interest

The author declares that they have no conflict of interest.

Data and materials availability

All data associated with this study are present in the paper.

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