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Evaluating the Potentials of Liberation Size Determination in Anka (Zamfara State, Nigeria) Manganese Ore and its Communition Tendency using Bond Index Technique

Y. E. Gbadamosi[1*], O. O. Alabi[1] and J. O. Borode[1]

[1]Metallurgical and Materials Engineering Department, School of Engineering and Engineering Technology, Federal University of Technology, P.M.B-704, Akure Ondo State, Nigeria.

Authors' contributions

This work was carried out in collaboration among all authors. Author YEG designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors OOA and JOB managed the analyses of the study. Authors YEG and JOB managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

The present level of exploitation of Manganesemineral from its ore is very low due to depletion of its ore; therefore, there is need for appropriate processing technique that will help in providing solution to the exploitation problem encountered. Chemical, Petrological, Mineralogical, Fractional sieve size analysis and work index of the Anka manganese ore in Anka town of Zamfara state, Nigeria was investigated. 500 g of the ore was weighed using digital weighing balance. The sample was crushed and ground to 80 % passing 250μm sieve size. The ground ore was analyzed using the Energy dispersive X-ray fluorescence spectrometer (ED-XRFS), X-ray Diffractometer (XRD), Scanning electron microscope equipped with dispersion spectrum analyzer (SEM-EDX) and Leica Petrological Microscope. Fractional sieve analysis of the crude sample was carried out at sieve range of 1000-63μm towards particle size distribution and liberation size determination. 500 grams of manganese ore and quartz were sampled and prepared by crushing and grinding to 100%

**Corresponding author: Email: gbadamosiyemisi.e@gmail.com;*

passing 1200μm sieve. 100 grams of prepared ores were charged into array of sieve arranged in √2 series. Set of sieves were mounted on automated Endecott sieve shaker and was operated for 20 minutes. ED-XRFS results shows 77.81% MnO, 10.9% Fe_2O_3, 4% Al_2O_3 while the mineralogical analysis reveals Spessartine ($3MnO.Al_2O_3$, 0.830), Silicon oxide (SiO_2, 1.122), Quartz (SiO_4, 0.728), Pyrolusite (MnO, 1.543), and Almandine ($Fe_3Al_2SiO_{12}$, 1.583) were identified as the major phases in the ore and the petrological analysis of the crude samples reveals the presence of heavy mineral and segregation distribution of the mineral. The particle size analysis carried out on the Anka Manganese ore revealed that the manganese bearing mineral can be liberated at the particle size fraction of -180 + 125 μm. The work index of the Anka Manganese ore was found to be 14.16 Kwh/ton using the Gaudin Schumann Expression and it falls within the range indicated in literatures as standard which is 10-15.14 Kwh/ton.

Keywords: Manganese; communition; liberation size; bond work index; particle size.

1. INTRODUCTION

World production of manganese (Mn) ore in 2010 rose by 26% on a gross weight basis, and by 31% on a contained weight basis, compared to that in 2009 [1]. Nevertheless, the current worldwide Manganese production is still unable to cope with the demand from the growing metallurgical industry. It is reported that metallurgical applications of manganese consume 77% to 90% of the total Manganese ore production [1]. Manganese is mainly used as a deoxidizer and desulfurizer in steel making, and as an important component in alloy-making. Other than that, additional quantities of manganese were used for non-metallurgical purposes such as a component in dry cell batteries, an additive in plant fertilizers and animal feed, as well as a colorant (for bricks) in the production of masonry [1]. As reported in Mineral Commodity Summaries (2012), no satisfactory substitute exists for replacing Manganese with other metals in its major applications. As the number of products from Manganese applications continues to rise, the demand for Manganese continues to increase. However, the metal's supply remains limited. Due to that, the price of Manganese escalated over the years, and some deposits, which were previously considered low-grade, can now be economically mined [2,3,4].The term manganese ore is used to describe ores assaying more than 35% Mn, while ores containing 10-35% Mn are termed ferruginous manganese ores and those containing less than 10% Mn are known as maganiferrous iron ores (Gupta, 2006). The end use manganese concentrates are classified into three types: Blast Furnace Grade (25 to (-) 35% Mn), Battery/ Chemical Grade (Mininum of 72% Mn), Ferromanganese Grade (Min of 38% Mn) and Medium Grade (35-37%) [5].

It is therefore important to characterize an ore in order to establish the relationship between structures of materials, the processing techniques of materials and the properties of materials/performance of material by describing the features of the composition and structure of material which is significant to the study of the properties, processing methods and application. In the exploitation of any mineral, it is important to understand the main inherent properties and composition which determine their behaviour during processing [6]. In addition, the characteristics of minerals also often determine the economical aspect of commercial exploitation of the mine site.

1.1 Work Index Determination

The work index is the energy required to reduce a given material from theoretical infinite size to 80% passing size of 100 μm and the Bond index method is useful in designing of grinding system as its parameters are used to measure ore grindability which involve the use of a test ore and reference ore (Adeoti *et al*., 2019). It is important to know the grinding characteristics of an ore so that suitable power can be selected for its comminution process. There are many theories of comminution, but this work uses the modified Bond's equation to determine the work index of the ore and it's mathematically expressed as:

$$W = Wit = Wir = \left(\frac{10}{\sqrt{P}} - \frac{10}{\sqrt{F}}\right) \quad (1)$$

$$Wit = Wir \times \left(\frac{\frac{10}{\sqrt{Pr}} - \frac{10}{\sqrt{Fr}}}{\frac{10}{\sqrt{Pt}} - \frac{10}{\sqrt{Ft}}}\right) \quad (2)$$

Where;

Wit = Work Index of test ore
Wir = Work index of reference ore
Pr = Diameter of the reference ore through which 80% of the product passes through 100μm

Pt= Diameter of the test ore through which 80% of the product passes through 100μm
Fr = Diameter of the reference ore through which 80% of the feed passes through 100μm
Ft = Diameter of the test ore through which 80% of the feed passes through 100μm
Wr = Work input for the reference ore.
Wt = Work input for the test ore (Adeoti *et al*., 2019).

The Anka mine site is located in the Anka is a Local Government Area in Zamfara State, Nigeria which is the northern axis of Zamfara state bounded by the geological coordinates, latitude 12°06'30"N and longitude 5°56'00"E and it's a reserve which is still under investigation by the Nigerian Geological Survey (NGS) . It has an area of 2,746 km^2 and a population of 142,280 at the 2006 census [7].

Hence, this research is aimed at determination of Anka Manganese liberation size and energy expended in comminutingthe ore using Bond work index method, leading to the determination of the parameters required for the design of machine needed for communition process of the ore to its liberation size.

2. MATERIALS AND METHODS

The material employed for the research work was the crude sample of Anka manganese ore, Zamfara State, Nigeria. The procedure adopted for the research work includes: sample collection and preparation, which was followed by the determination of the physical and chemical characteristics and grindability test, leading to work index determination.

2.1 Sample Collection

Anka manganese samples were sourced from 10 different pits, dug at a dimension of 1.0 meter by 1.0 meter by 2.0 meter. The collected samples were properly mixed to obtain homogenization from which 50 kg were weighed using cone and quartering sampling technique. 20 kg of the as received crude was sampled out for the research work.

2.2 Sample Preparation

20 kg of crude sample collected was crushed using the Fritsch Pulveristte Laboratory Jaw Crusher (Model LF6797AC, Size: D-12) and the crushed product was then ground in a Denver Laboratory Milling Machine (Ball mill) for characterization analysis and for liberation size determination.

2.3 Chemical Characterization of the Anka Manganese Ore Sample

Chemical characterization of the crude was carried out using Energy Dispersive X-ray Fluorescence Spectrometer (ED-XRFS). 20 g of the manganese ore sample was finely ground to pass through a 200-250 mesh sieve. Thereafter, the sample was intimately mixed with a binder in the ratio of 5.0 g sample(s) to 1.0 g cellulose flakes binder and pelletized at a pressure of 10-15 $tons/inch^2$ in a pelletizing machine. At this stage, the pelletized sample(s) were stored in a desiccator for analysis. The machine ED-XRFS (Model: PANanalytical Minipal 7), was switched on and allowed to warm up for 2 hours. Finally, appropriate programs for the various elements of interest were employed to analyze the sample material(s) for their presence or absence. The result of analysis was reported in percentage (%) for minor and major concentrations of elements (Table 1).

2.4 X-ray Diffractometer (XRD) Analysis of the Anka Manganese Ore Sample

The sample was prepared for XRD analysis and was analyzed using a PANalyticalX'Pert Pro powder diffractometer with X'Celerator detector and variable divergence and receiving slits with Fe filtered Co-Kα radiation. The phases were identified using X'Pert Highscore plus software. The receiving slit was placed at 0.040°. The counting area was from 5 to 70° on a 2θ scale. The count time was 1.5 s. The temperature-scanned XRD data were obtained using an Anton Paar HTK 16 heating chamber with Pt heating strip Graphical representations of the qualitative result follow below. The relative phase amounts (weight %) was estimated using the Rietveld method.

2.5 Scanning Electron Microscope Equipped with Dispersion Spectrum Analysis (SEM-EDX) of the Anka Manganese Ore Sample

Morphology and microanalysis of the crude Anka manganese ore was determined using ultra-high resolution field emission scanning electron microscope (UHR-FEGSEM) equipped with energy dispersive spectroscopy (EDS). The pulverized crude sample was studied using ultra-high resolution field emission scanning electron microscope (UHR-FEGSEM) equipped with energy dispersive spectroscopy (EDS). Particle image was obtained with a secondary electron detector.

2.6 Petrological Analysis of the Anka Manganese Ore Sample

A chip of about 1/8 of an inch and about 1 inch by 1 inch was cut from the lumps of Anka manganese sample using rock cutter, after which their surfaces were trimmed and the chip was mounted on a grinding machine to make the surface smooth. The samples were mounted on a slide and viewed using Leica Petrological Microscope to determine the microstructure of the ore at a satisfactory magnification and image display and the different minerals were identified.

2.7 Fractional Sieve Size Analysis of the Anka Manganese Ore Sample

The fractional sieve analysis of 100 g head sample was carried out using sieves of size range of 1000 µm to - 63 µm of $\sqrt{2}$ series to evaluate the liberation size of the valuable mineral [8,9]. The sample was charged into the upper sieve and the sieve sets were agitated for 30 minutes using an Automated Pascal Denver sieve shaker (16153). The undersize particles fall through successive sieves until they were retained on a sieve having apertures which are slightly smaller than the diameter of the particles. The set of sieves were separated and the weight retained of each sieves was recorded. The data obtained were used to compute the sieve analysis table (Table 2) along side with a plot of log of percentage cumulative retained and passing against sieve sizes (µm) (Fig. 4). Chemical analysis of each sieve size fractions was also carried out and result obtained revealed the actual liberation size.

2.8 Bond Index Determinations of the Anka Manganese Ore

The work index of Anka manganese ore sample was determined using the modified Bond's method of Gaudin Schumann Expression. Quartz ore sourced from Anka Zamfara State mine site was used as the reference ore. The reference ore was broken with a sledge hammer manually to produce feed which was charged into the Fritsch Pulveristte Laboratory Jaw Crusher (Model LF6797AC, Size: D-12). The product of the jaw crusher was further pulverized in the Denver Laboratory Milling Machine (Size: D-12). Both the test and reference ore were subjected to the same crushing and grinding processes. 100 g each of the samples (test and reference ore) was charged into the set of sieves which was placed on the Automated Pascal Denver sieve shaker (16153) which vibrates the sieve in a vertical plane for 20 minutes and each sieve fraction retained of the test and reference ore were weighed. 100 g each from the milled product was also charged into the set of sieves which was placed on the Automated Pascal Denver sieve shaker (16153) which vibrates the sieve in a vertical plane for 15 minutes and each sieve fraction retained of the test and reference ore were weighed. The results obtained were calculated to establish the amount of energy needed to reduce the mineral to its liberation size.

3. RESULTS AND DISCUSSION

3.1 Results

The results obtained are presented in Tables 1- 6 and Figs 1- 4.

3.1.1 Evaluation of grindability

$R = \frac{F}{P}$

Where,

R = Reduction Ratio
F = Diameter of feed particles
P = Diameter of product particles
Using Gaudin Schumann Expression

$P(X) = 100\ (X \div K)^{\alpha}$

$$\alpha = \frac{\log P\ (X2) - \log P\ (x1)}{\log\ (X2) - (X1)} \quad (3)$$

$\text{Sieve } 1 = \frac{\%\, passingsieve\ 1}{\%\, passingseive\ 2} \times \text{Sieve } 2$

X = Sieve mesh size with 80% of particle size passing
Quartz (Reference Ore)

From the feed to the ball mill at sieve mesh 500 µm, 69.16% of grain size passed through.

For 80% passing: $Fr = \left(\frac{80}{69.16}\right)^2 \times 500 = \left(\frac{0.80}{0.6916}\right)^2 \times 500 = 1.157^2 \times 500 = 663.5$ µm

Product of reference ore from the ball mill 82.21% passes through the 250 μm sieve size

For 80% passing: $Pr = \left(\frac{80}{82.21}\right)^2 \times 250 = \left(\frac{0.8}{0.8221}\right)^2 \times 250 = 0.973^2 \times 250 = 253.75$ μm

Anka Manganese Ore (Test Ore)

From the feed to the ball mill at sieve mesh 500 μm, 73.64 % of grain size passed through.

For 80% passing: $Ft = \left(\frac{80}{73.64}\right)^2 \times 500 = \left(\frac{0.8}{73.64}\right)^2 \times 500 = 1.087^2 \times 500 = 591$ μm

Product of test ore from the ball mill 79.48% passes through the 250 μm sieve size

For 80% passing: $Pt = \left(\frac{80}{79.48}\right)^2 \times 250 = \left(\frac{0.8}{0.7948}\right)^2 \times 250 = 1.007^2 \times 250 = 236.75$ μm

Work index determination

$W = Wit = Wir = \left(\frac{10}{\sqrt{P}} - \frac{10}{\sqrt{F}}\right)$

$Wit = Wir \times \left(\frac{\frac{10}{\sqrt{Pr}} - \frac{10}{\sqrt{Fr}}}{\frac{10}{\sqrt{Pt}} - \frac{10}{\sqrt{Ft}}}\right)$

Where, $Wir = 14.1 = 14.1 \times \left(\frac{\frac{10}{\sqrt{253.75}} - \frac{10}{\sqrt{663.5}}}{\frac{10}{\sqrt{236.75}} - \frac{10}{\sqrt{591}}}\right) = 14.16$ Kwh/ton

Energy expended in grinding determination

$Wt = 10Wit \times \left(\frac{1}{\sqrt{236.75}} - \frac{1}{\sqrt{591}}\right) = 10 \times 14.16 \times \left(\frac{1}{\sqrt{236.75}} - \frac{1}{\sqrt{591}}\right) = 3.3984$ Kwh

Table 1. Chemical composition of crude Anka manganese ore

Al_2O_3	SiO_2	K_2O	CaO	TiO_2	V_2O_5	MnO	Fe_2O_3
4.0	4.8	0.32	0.949	0.30	0.12	77.81	10.9

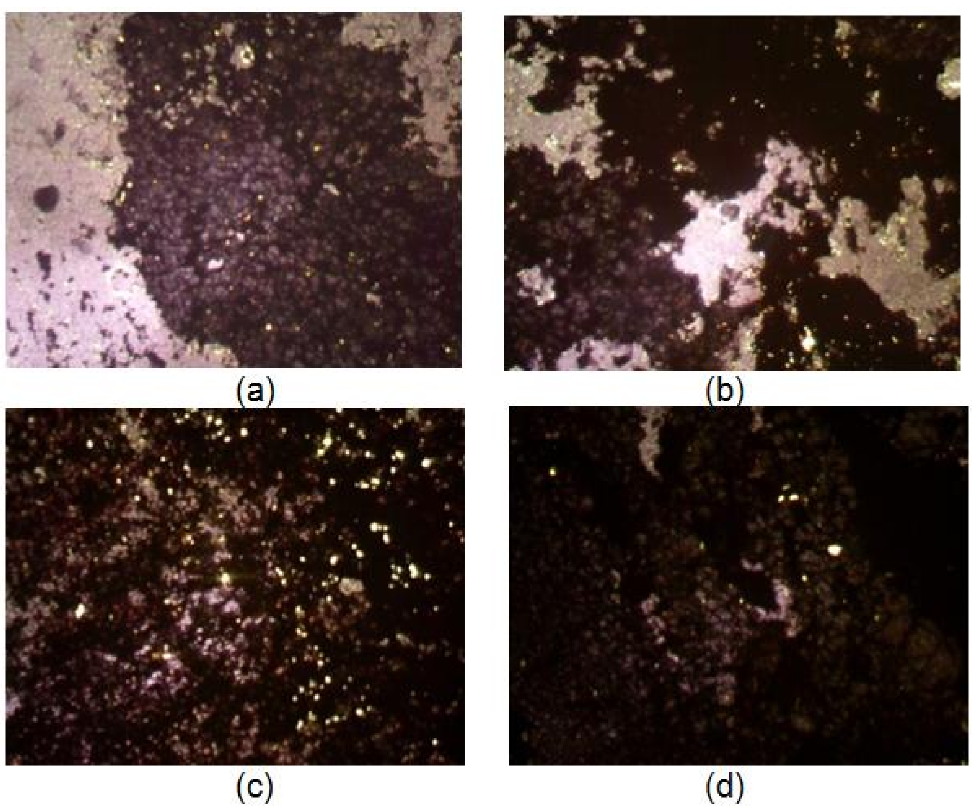

Fig. 1. (a,b,c,d). Photomicrographs of crude Anka manganese Ore

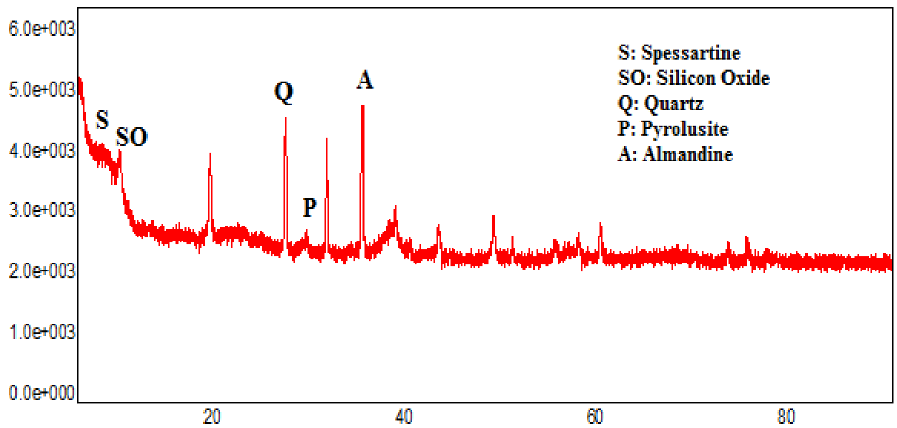

Fig. 2. X-rays Diffractometer (XRD) of Crude Anka Manganese Ore

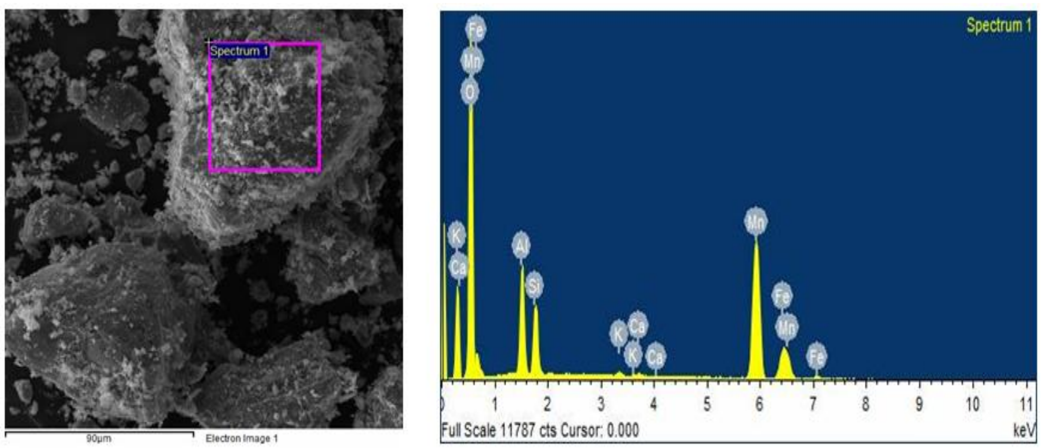

Fig. 3. SEM Image showing the ore microstructure at (90 µm) and EDS analysis

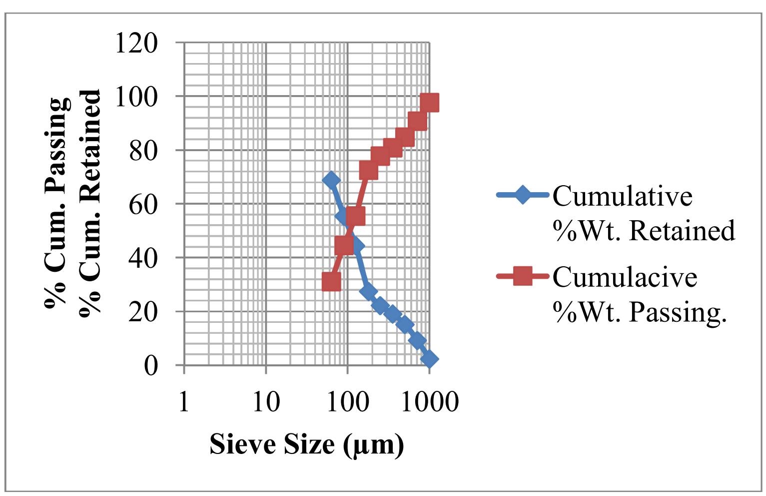

Fig. 4. A plot of log of percentage cumulative retained and passing against sieve sizes (µm) of the fractional analysis of manganese Ore

Table 2. Fractional sieve size analysis of crude Anka manganese ore

Sieve size range	Weight retained (g)	% Weight retained	Cumulative weight retained	Cumulative weight passing	MnO%
+1000	2.20	2.33	2.33	97.67	76.78
-1000+710	6.50	6.88	9.21	90.79	75.21
-710+500	5.60	5.93	15.14	84.86	75.44
-500+355	3.70	3.92	19.06	80.94	73.78
-355+250	2.97	3.14	22.20	77.80	74.82
-250+180	4.93	5.22	27.42	72.58	77.46
-180+125	16.07	17.01	44.43	55.57	77.50
-125+90	10.40	11.01	55.44	44.56	75.91
-90+63	12.67	13.41	68.85	31.15	75.43
-63	29.43	31.15	100	0	73.15

Table 3. Sieve analysis of quartz (reference ore) feed to the ball mill

Sieve size range	Weight retained (g)	% Weight retained	Cumulative weight retained	Cumulative weight passing
+1000	0.70	0.71	0.71	99.29
-1000+710	1.60	1.62	2.33	97.67
-710+500	28.20	28.51	30.84	69.16
-500+355	18.70	18.91	49.75	50.25
-355+250	13.30	13.45	63.20	36.80
-250+180	10.20	10.31	73.51	26.49
-180+125	13.50	13.65	87.16	12.84
-125+90	5.20	5.26	92.42	7.52
-90+63	5.0	5.06	97.48	2.52
-63	2.5	2.52	100	0

Table 4. Sieve analysis of anka (zamfara state) manganese ore (test ore) feed to the ball mill

Sieve size range	Weight retained (g)	% Weight retained	Cumulative weight retained	Cumulative weight passing
+1000	2.50	2.51	2.51	97.49
-1000+710	1.50	1.50	4.01	95.99
-710+500	22.30	22.35	26.36	73.64
-500+355	16.40	16.43	42.79	57.21
-355+250	12.30	12.32	55.11	44.89
-250+180	9.70	9.72	64.83	35.17
-180+125	9.30	9.32	74.15	25.85
-125+90	7.60	7.61	81.76	18.24
-90+63	10.10	10.12	91.88	8.12
-63	8.10	8.12	100	0

Table 5. Sieve analysis of quartz (reference ore) product from the ball mill

Sieve size range	Weight retained (g)	% Weight retained	Cumulative weight retained	Cumulative weight passing
+1000	-	-	-	-
-1000+710	-	-	-	-
-710+500	0.70	0.70	0.70	99.30
-500+355	1.60	1.61	2.31	97.69
-355+250	15.40	15.48	17.79	82.21
-250+180	12.40	12.46	30.25	69.75
-180+125	16.80	16.88	47.13	52.87
-125+90	16.30	16.38	63.51	36.49
-90+63	15.30	15.38	78.89	21.11
-63	21.00	21.11	100	0

Table 6. Sieve analysis of anka manganese ore (test ore) product from the ball mill

Sieve size range	Weight retained (g)	% Weight retained	Cumulative weight retained	Cumulative weight passing
+1000	-	-	-	-
-1000+710	-	-	-	-
-710+500	0.60	0.60	0.60	99.4
-500+355	1.20	1.21	1.81	98.19
-355+250	18.60	18.71	20.52	79.48
-250+180	12.40	12.47	32.99	67.01
-180+125	16.20	16.30	49.29	50.71
-125+90	15.30	15.40	64.69	35.31
-90+63	16.50	16.60	81.29	18.71
-63	18.60	18.71	100	0

3.2 Discussion

Table 1 shows the result of the chemical compositional analysis of crude Anka manganese ore and reveals that MnO is the highest chemical compound present, having 77.8 % MnO with 10.9% Fe_2O_3, 4% Al_2O_3, 4.8% SiO_2, and other constituent compounds. Binta *et al.*, [10] emphasized that 52.50% Mn can be accommodated or accepted for the production of ferromanganese alloys for iron and steel companies. The result obtained further showed that the Anka Manganese ore meet the metallurgical required grade of not less than 50 % Mn (66% MnO) and it's a complex ore of oxide and silicate [11]. This shows the ore as a potential source of Manganese metal and when extracted can be added to steel as alloying element [12].

Fig. 1 present the photomicrographs of the petrological analysis carried out on the crude Anka manganese ore and it reveals the presence of heavy mineral (Mn, Fe) and light minerals (Quartz) and it further shows the distribution (Evenly distribution, Sparingly distribution) of the minerals in the matrix of the ore. It is clearly seen that the heavy minerals is dominated in the ore matrix.

Fig. 2 presents the mineralogical assemblage of manganese ore via XRD. The diffractogram shows the peaks of different minerals present within the ore matrix and their relative figure of merit. The minerals present and their relative figure of merit are as follows: Spessartine ($3MnO.Al_2O_3$, 0.830), Silicon oxide (SiO_2, 1.122), Quartz (SiO_4, 0.728), Pyrolusite (MnO, 1.543), and Almandine ($Fe_3Al_2SiO_{12}$, 1.583). From the diffractogram, Anka Manganese ore is a complex and metallurgical manganese ore composed of spessartine quartz, and pyrolusite.

Fig. 3 presents the SEM image at 90 magnification and EDS qualitative analysis of the image for the Anka manganese ore and the SEM micrograph reveals that the minerals present in the ore matrix are closely packed which will enhance easy liberation via comminution. The EDS qualitative analysis of the image clearly revealed the presence of Fe, Mn, O, K, Ca, Al, and Si. The point analysis carried out further reveals that oxygen, iron and silica are the predominant elemental constituents of minerals in the ore matrix.

Table 2 and Fig. 4 shows the result of the fractional sieve size analysis of crude Anka manganese ore and the plot of log of percentage cumulative retained and passing against sieve sizes (µm) of the fractional analysis of Manganese Ore. Table 2 reveals the quantity the weight retained in each sieve fraction and the cumulative percentage passing following the order of sieve arrangement from the coarsest is obtained as 97.67 %, 90.79 %, 84.86 %, 80.94 %, 77.8 %, 72.58 %, 55.57 %, 44.56 %, and 31.15%.The table also shows the chemical analysis of the ore sample conducted on all the sieve size fractions. The result in its elemental form indicate the percentage composition of manganese in oxide and metal constituent in each of the sieve sizes which is as follows; +1000 µm (76.78 % MnO), -1000 +710 µm (75.21 % MnO), -710+500 µm (75.44 % MnO), -500 +355 µm (73.78 % MnO), -355 +250 µm (74.82 % MnO), -250 +180 µm (77.46 % MnO), -180 +125 µm (77.50 % MnO), -125 +90 µm (75.91 % MnO), -90 +63 µm (75.43 % MnO), and -63 µm (73.15 % MnO).

Significant liberation of mineral of interest (manganese) was achieved at sieve size fraction of -180 +125µm with percentage assay of 77.50 % MnO being the highest percentage of manganese when compared to other sieve sizes. This indicates that reasonable quantity of Mn can be obtained if the ore is ground to -250 +180 µm when compared to other sieve fractions. Hence, -250 +180 µm is the liberation size of Anka manganese ore.

Fig. 3 shows that the two curves which are mirror image of each other intercepted at -180 + 125 µm which is in agreement with the result of the chemical analysis of sieve fractions. -180 + 125 µm has the highest assay. Therefore, -180 + 125 µm is the liberation size for Anka Manganese ore.

Table 3 - 6 present the result of the grindabilty test of Anka Manganese ore (Test ore) and Quartz (Reference ore). The result revealed that 80% passing particle size fractions for feed to the ball mill (Fr, Ft) of both the reference ore and test ore was found to be 663.5 µm and 591 µm, likewise the 80% passing particle size fractions for product from the ball mill (Pr, Pt) of both the reference ore and test ore was found to be 253.73 µm and 236.75 µm respectively. The work index of the Anka Manganese Ore was computed to be 14.16 Kwh/ton and the value obtained means that 14.16 Kwh/ton of energy is

required to reduce one ton of the Anka Manganese ore sample from 80% passing size. The work index of the Anka Manganese ore was found to be 14.16 Kwh/ton and it falls within the range indicated in literatures as standard which is 10-15.14 Kwh/ton [12,13].

4. CONCLUSION

The ED-XRFS analysis shows the presence of manganese with the highest assay in the ore, thepetrological analysis and SEM/EDX study, show that the manganese mineral was found interlocking in quartzand themanganese was also found to be evenly disseminated on the silicatemineral surface like quartz (SiO_2) and other mineral as also confirmed by thechemical characterization. The mineralogical study using XRD shows that anka manganese ore is a complex ore and a metallurgical manganese ore composed of spessartine quartz, and pyrolusite. Also, the actual liberation size was determined to be -180 + 125 μm, and the work Index of Anka manganese ore from Anka mine site in Zamfara state, Nigeria has been determined and found to be 14.16 kwh/ton. Also the energy expended was computed to be 3.3984 Kwh. This parameter serves help for the development of a processroute for the beneficiation of Anka manganese ore to the economic and technological development of a nation.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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