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CHEMICAL, MINERALOGICAL, AND GRINDABILITY STUDIES OF ANKA-BRABRA COPPER ORE

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ABSTRACT: *This study examined the chemical characteristics, mineralogy, and grindability of copper ore from Anka-Brabra, Zamfara State, Nigeria. The ore was crushed, ground, and mixed to achieve a uniform sample. The ore sample was characterised using EDX-XRF, XRD, SEM, and petrological microscope. Grindability and fractional sieve analysis techniques were used to ascertain optimal grinding size through particle size distribution and the liberation size of the mineral. Results showed the main copper mineral was malachite ($Cu_2(CO_3)(OH)_2$) with traces of other minerals. Analysis indicated a copper content of up to 20.2%. The ideal grinding size for liberation was determined to be 160 microns, with 53% of the ore particles reaching an acceptable size of 250 microns. The ore sample was characterised using EDX-XRF, XRD, SEM, and petrological microscope. Grindability and fractional sieve analysis techniques were used to ascertain optimal grinding size through particle size distribution and the liberation size of the mineral.*

KEYWORDS: Copper ore, Grindability, Work Index, Liberation Size.

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INTRODUCTION

Rapid urbanization and the shift to renewable energy sources have increased the demand for copper, a crucial metal for contemporary infrastructure and technology (Chalker, 2019). However, the supply of easily accessible high-grade copper deposits is running low, thus lower-grade ores must be extracted. It is extremely difficult to process these low-grade resources because of the ore's peculiarities and how it reacts to grinding (comminution) techniques. So, there is a need to study the grindability, chemical, and mineralogical characterization of these ores to understand their physical and chemical properties of the ores.

Characterization study is very important because it comprehensively analyses the physical and chemical properties of the low-grade copper ore. This includes determining the mineralogical composition and identifying the copper-bearing minerals and their associations with gangue minerals (waste rock). Techniques like X-ray diffraction (XRD) and Scanning Electron Microscopy (SEM) with Energy Dispersive Spectroscopy (EDS) provide valuable insights into the mineral phases present, their grain sizes, and elemental distribution. Knowledge of the ore's chemistry, obtained through assays, reveals the total copper content and the presence of any harmful elements that may impact processing or product quality.

Furthermore, the initial step involves characterising the ore's textural properties, such as the degree of fracturing and porosity (Wills & Finch, 2015). These aspects significantly influence the ease of grinding and the liberation of copper minerals from the surrounding gangue (waste rock) (Ojo & Olaleye, 2000; Wang *et al.,* 2020; Wills & Finch, 2015). Techniques like image analysis and mercury intrusion porosimetry can be employed to quantify these crucial properties (Guo *et al.,* 2021; Nguyen & Foucaud, 2014).

Following characterization, grindability studies delve into how the ore responds to mechanical size reduction. A key parameter often determined is the Bond Work Index, which quantifies the energy required to grind a specific mass of ore to a standard fineness (Bond, 1961; Asbjörnsson, 2022; Hosseini *et al.,* 2022). Lower work indices indicate a more easily grindable ore, translating to lower energy consumption during processing (Fuerstenau & Han, 1982; Nzeh *et al.,* 2023; Ghadiri *et al*., 2019). Grindability studies also explore how particle size distribution (PSD) evolves with grinding intensity (Nghipulile *et al.*, 2023). Techniques like sieve analysis and laser diffraction measure the size distribution of the crushed and ground ore at different stages (Gao *et al.*, 2020; 2020; Riener *et al.*, 2020). This data helps determine the optimal grinding target size – the size at which sufficient liberation of copper minerals occurs without generating excessive fines (Fuerstenau & Han, 1982). Excessive fines can hinder downstream processing steps such as flotation, where copper is separated from the gangue (Bahrami *et al.,* 2022).

The significance of characterization and grindability studies extends beyond optimising the comminution circuit. Understanding the ore's behaviour allows for the selection of appropriate grinding techniques. Traditional ball mills may not be the most energy-efficient option for all low-grade copper ores. Newer technologies, such as high-pressure grinding rolls (HPGRs) or autogenous grinding (AG), may offer better liberation efficiency at lower energy costs depending on the ore characteristics (Rodriguez *et al.,* 2024; Van De Vijfeijken *et al.,* 2024).

Furthermore, these studies provide valuable data for designing a sustainable and environmentally friendly processing flowsheet. Minimising energy consumption during grinding reduces the overall carbon footprint of copper production (Morrell, 2022; Jose-Luis *et al.,* 2019). Additionally, optimising the liberation process minimises the generation of waste fines, leading to more efficient downstream processing and potentially lowering tailing disposal volumes (Hanumanthappa *et al.,* 2020).

Studies on grindability are essential for determining cost and efficiency in copper mining and processing. The comminution circuit, which crushes and grinds the ore into smaller bits for further processing, is designed with the ore's grindability—or ease of grinding—into consideration (Ali *et al.,* 2020; Leon, 2024). Simpler ore grinding means less energy use and less wear and tear on grinding equipment, which adds up to big financial savings (Adewuyi *et al.,* 2022; Beaucamp *et al.,* 2020.). Additionally, research on grindability offers information on the energy needed to produce the appropriate particle size for the extraction of copper (Chimwani, 2024; Zhang *et al.,* 2023). This makes it possible to optimise the parameters of the grinding process, such as feed size, media load, and mill speed. Appropriate optimization reduces energy waste and guarantees effective copper recovery (Chimwani, 2024; Zhang *et al.,* 2023).

For effective extraction, copper minerals must be freed from gangue minerals or waste rock (Hernandez *et al.,* 2020). Studies on grindability aid in identifying the ideal size for grinding that releases the copper minerals without producing unduly fine particles, which may be challenging to separate at a later stage (Park & Moon, 2020). Because grindability studies maximise copper recovery, minimise equipment wear, and optimise energy use, they enable copper mining operations to achieve an efficient and economical process (Wang *et al.,* 2020). For this reason, they are crucial.

Luís (2020) studied the comminution and liberation response of iron ore types in a low-grade deposit. The samples were subjected to chemical and mineralogical composition, liberation characteristics, scanning electron microscopy and QEMSCAN. Samples were also subjected to point-load and abrasiveness tests as well as batch grinding tests. It is evident that at coarse sizes the ore types present significantly different strengths and abrasiveness, with values decreasing, as expected, with increasing degree of weathering. However, such differences partially disappeared as comminution progressed to finer sizes. The amenability of the different ores to slime generation also varied, with weathered ores presenting significantly higher values. Grade-by-size deportment results show that selected ore types offer the opportunity for early gangue (silica) rejection before the grinding stage.

Characterization and grindability studies are fundamental steps in processing low-grade copper ores. By gaining a comprehensive understanding of the ore's composition, texture, and response to grinding, mining operations can optimise their processes for efficient copper recovery, minimise energy consumption, and contribute to a more sustainable future for the copper industry.

Despite all investigations, significant knowledge gaps remain regarding the characterization of specific complex copper ore deposits (Gholami *et al.,* 2021). The characterization of a specific copper ore deposit by conducting detailed mineralogical, geochemical, and liberation studies to understand the ore's composition, texture, and liberation characteristics is very germane in ore concentrations. This study's thrust centres on the fact that chemical, mineralogical, and grindability studies of Anka-Brabra copper ore are not common in the literature.

METHODS

Sample Collection and Preparation

Copper ore and granite (reference ore) were sourced from the Anka-Brabra local government area of Zamfara State with geological coordinates of 12°06′30″N and 5°56′00″E. The as-mined sample was first reduced to 50 mm size with a hammer before being charged into the Denver laboratory jaw crusher for further reduction to 5 mm. The sample was further reduced to about 1 mm via the smaller laboratory jaw crusher after which thorough mixing was carried out to obtain a homogenised sample. The conning and quartering method was used to divide the sample into four equal parts.

Chemical Characterization using ED-XRF

Chemical characterization of the crude was carried out using Energy Dispersive X-ray Fluorescence Spectrometer (PAN analytical Minipal 7). Twenty (20) grams of the 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 5 of 10-15 tons/inch2 in a pelletizing machine. At this stage, the pelletized sample(s) are stored in a desiccator before analysis. The ED-XRF machine was allowed to warm up for 2 hours after switching it on before the samples were introduced to it. Finally, appropriate programs for the various elements of interest were employed to analyse the sample material(s) for their presence or absence. The result of the analysis was reported in percentage (%) composition for trace and major concentrations of elements.

Mineralogical Characterization using XRD

Qualitative and quantitative determination of the nature of the phases and the amount of the phases present in the sample were determined by a PANalytical Empyrean diffractometer with Pixel-detector and fixed slits with Fe-filtered Co-Kα radiation. The material was prepared for XRD analysis using a backloading preparation method. The phases were identified using X' Per High score plus software. The relative phase amounts (%weight) were evaluated using the Rietveld method.

Mineralogical Characterization using SEM/EDS

Morphological and qualitative analyses of the bulk ore were performed using SEM-EDS. The SEM provides information on the spatial distribution of mineral phases present in the crude, while EDS provides information on their elemental composition. Mineralogical analysis via SEM-EDS was conducted on representative samples in two stages using SEM (Model: JEOL 840). All the samples were carbon-coated to make the mineral's surface conductive. Samples for analysis were cut, polished mounts in embedded epoxy resin, and finally polished to obtain a mirror-like surface. The polished surfaces were finally carbon-coated before analysis. Qualitative chemical analysis of the samples was carried out using an EDS detector attached to the SEM.

Petrological Analysis

Samples were cut from the Anka-Brabra copper ore boulders to a standard size, after which their surfaces were ground using emery paper of grit size 500 µm and 1000 µm successively. The samples were mounted on a slide and viewed using a Leica Petrographic Microscope to determine the microstructure of the ore at a satisfactory magnification, the images were displayed, and the different minerals were identified, and grains were counted.

Grindability

Grindability of Anka-Brabra copper ore was carried out using the Berry and Bruce Method of Bond Work Index, granite from the same location was used as the test ore. The copper and granite samples were separately crushed in the jaw crusher and milled in the ball mill with steel balls weighing approximately 1 kg. 100 g of 1,400 µm samples were weighed for sieve analysis as feed for the test and the reference ore. The samples were thereafter gathered and returned to the Denver ball mill for 10 minutes, the product was then taken and sieved into different sieve sizes 1400, 1000, 710, 500, 355, 250, 180, 125, 90, 63 µm, and pan. The fractions were weighed, and the values were recorded as "feed" and "product" respectively. This procedure was repeated two times, and the average was determined.

Particle Size Analysis

The fractional Sieve Analysis technique was adopted to ascertain the particle size distribution and the liberation size of the mineral. The set of sieves was properly cleaned to avoid contamination of the mineral sample and arranged in conformity with √2 series ranging from 1400–63 µm (Wills, 2006). 100 grams of the crude sample were weighed and charged into the uppermost sieve (1400 µm) and agitated for 30 minutes using Pascal's Engineering Sieve Shaker. This consequently causes the undersized mineral particles to fall through successive sieves until they are retained on a sieve having an aperture lesser than their particle diameter.

RESULTS

The results of the chemical composition of Anka-Brabra ore are shown in Table 1.

Chemical Composition of Crude Anka-Brabra Copper Ore

The result of the chemical analysis of crude Anka-Brabra copper ore according to the Energy Dispersive X-ray Fluorescence Spectrometer (ED-XRF) is presented in Table 1. As reflected in the table, the ore contains 6.9% SiO_2, 0.7% SO_3, 20.73% Fe_2O_3, 66.65% CuO (i.e. 53.2% Cu), 1.49% ZnO, 0.16% CaO, 0.20% TiO_2, 0.12% Cr_2O_3, 0.43% ZrO_2, 0.97% BaO, 1.10% PbO, and other trace compounds. From the result, it can be deduced that the ore's matrix contains predominantly copper, iron, sulphur, lead, silicon, and zinc in oxide forms. The presence of zinc and lead oxides above 1% within the ore depicts the mineralization of the Pb-Zn-Cu phase in the Anka-Brabra deposit. This phenomenon could be ascribed to the geochemical formation of the deposit (Niu *et al.,* 2024).

Table 1: Chemical Composition of a Crude Sample of Anka-Brabra Copper Ore

Compounds	SiO_2	SO_3	CaO	TiO_2	Cr_2O_3	Fe_2O_3	CuO	ZnO	ZrO_2	Bao	PbO
% Comp.	6.9	0.7	0.16	0.20	0.12	20.73	66.65	1.49	0.43	0.97	1.10

*Comp. – Composition

According to Damisa (2008), lead-zinc-copper complex ores are situated within the Benue trough of which Niger state is located. From this finding, it can be inferred that Anka-Brabra copper ore is a high-grade copper ore assaying 53.2% Cu and can be profitably mined since it exceeds the 0.5% cut-off grade specified as standard for mining of copper mineral (Barani *et al.*, 2021; Ju *et al.*, 2021)

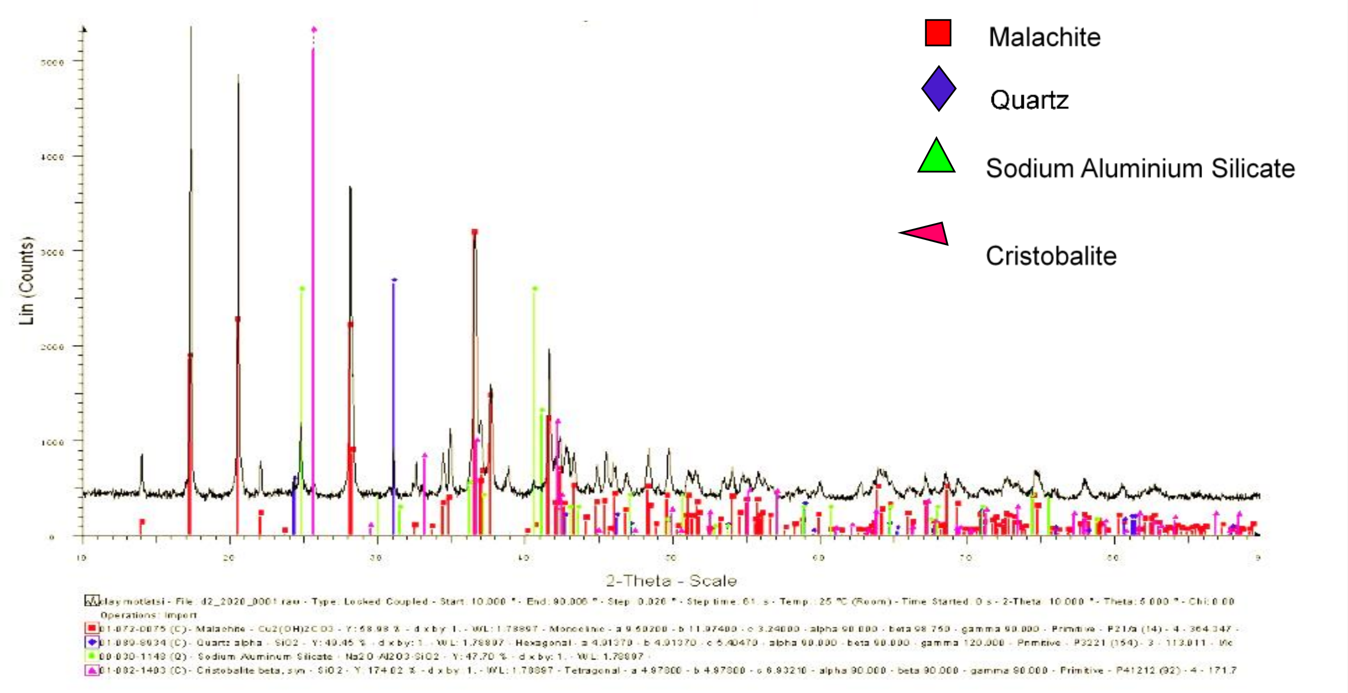

Figure 1: XRD Pattern of the crude sample of Anka-Brabra copper ore

XRD of Anka-Brabra Copper Ore

Figure 1 presents the XRD pattern of the crude sample of Anka-Brabra copper ore. The result revealed that the Anka-Brabra copper ore comprises virtually pure Cu-carbonate hydroxide in the form of the mineral malachite ($Cu_2(CO_3)(OH)_2$). There are also traces of sodium aluminium silicate ($Na_2O.Al_2O_3.SiO_2$) and two forms of silica (SiO_2), quartz and cristobalite. Thus, it can be inferred that the copper element in the Anka-Brabra deposit occurs as malachite alongside associated minerals. Hence, the need for the beneficiation of the ore to recover the copper mineral. The result obtained conforms to that of the XRF analysis which also affirmed that copper oxide is the predominant compound in the ore matrix.

SEM/EDX of Anka-Brabra Copper Ore

Figure 2 reveals the SEM images of the crude sample of Anka-Brabra copper ore captured at varying magnifications while Tables 2 and 3 reveal the EDS analysis of the ore and identified mineral grains respectively. It can be deduced from the micrographs that the ore contains grains of sodium aluminium silicate and copper carbonate hydroxide dispersed within a silica-dominated matrix. The EDS analysis of the ore affirmed the presence of copper (20.2%) within the ore matrix. Also, the elemental composition corresponds to what was determined by XRD, except for Fe and Ca. There were no traces of Fe or Ca-bearing phase(s) probably because they were below the detection limit of the XRD (~2% by volume) or, as suggested by semi-quantitative EDS analyses, the Cu-carbonate contains traces of Fe. The Ca may be present at low concentrations in the NaAl-silicate – XRD result suggests that this phase corresponds to the mineral albite ($NaAlSi_3O_8$).

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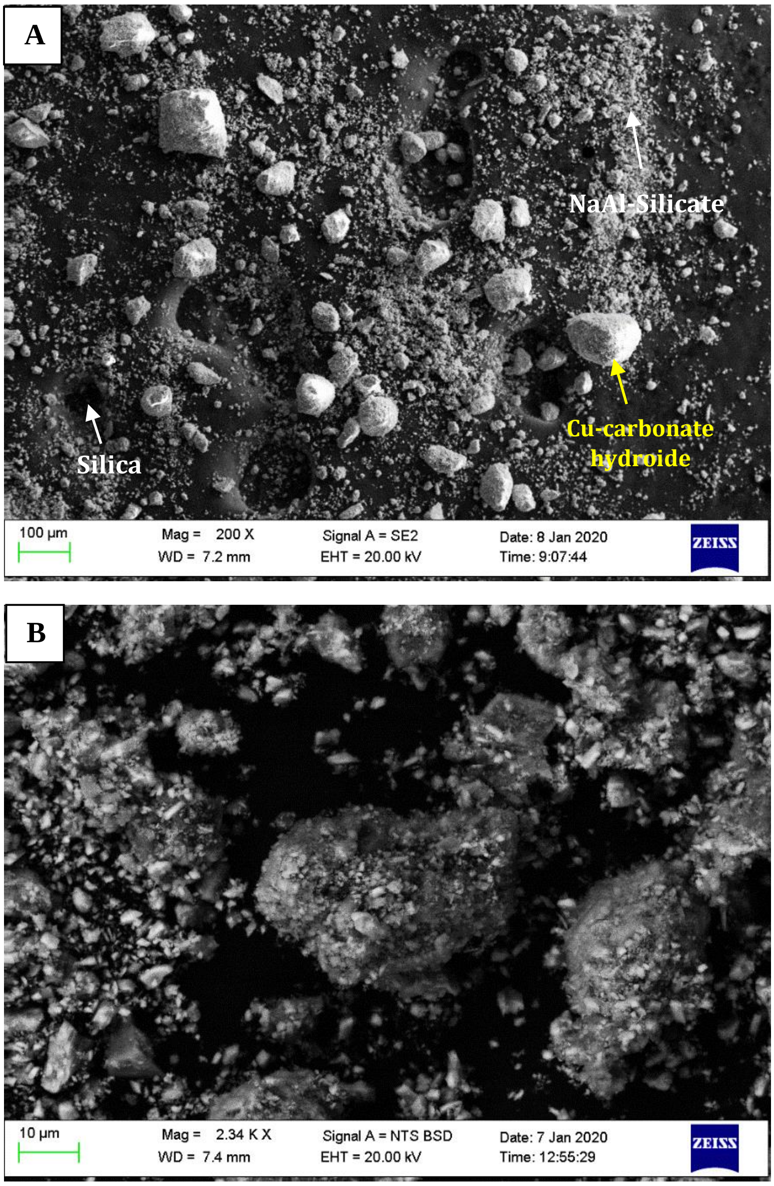


Figure 2: SEM Images of Crude Sample of Anka-Brabra Copper Ore at Different Magnifications using Back-scattered Electron

Table 2: EDS Analysis of the Crude Sample of Anka-Brabra Copper Ore

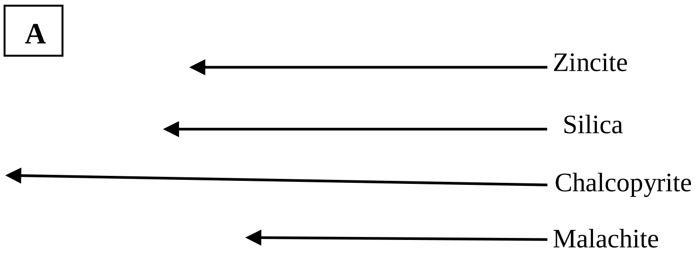
Element	Cu	C	Si	Na	Al	Fe	O	**Total**
%	20.2	38.4	1.8	0.3	0.9	4.1	34.3	**100**

Table 3: EDS Analysis of Identified Minerals in Anka-Brabra Copper Core's Matrix

Element	Cu-carbonate		NaAl-silicate	
	Cu-carbonate (EDS)*	Theoretical composition of the mineral malachite ($Cu_2(CO_3)(OH)_2$)	NaAl-silicate (EDS)	Theoretical composition of the mineral albite ($NaAlSi_3O_8$)
Cu	34.9	57.48		
C		5.43		
Si	5.1		24.6	31.50
Al	2.8		7.1	10.77
Na			6.5	8.30
Fe	10.3			0.76
H		0.91		
O	46.9	36.18	61.8	48.66
Total	100.0	100.00	100.0	100.00

*Used EDS without C as inaccurate with C. The Si and Al are being picked up from the surrounding matrix as the sample is fine-grained.

Petrological Analysis of Anka-Brabra Copper Ore



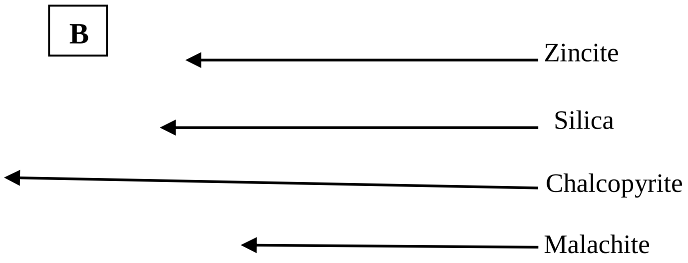


Plate 1: Micrograph of the Crude Sample of Anka-Brabra Copper Ore under Plane-Polarised Light at a Magnification of (a) X100, and (b) X2001

Plate 1 reveals the micrographs of the crude sample of Anka-Brabra copper ore at different magnifications. The ore matrix contains four mineral phases – chalcopyrite (brass-yellow), malachite (greenish-yellow), zincite (grey), and silica mineral (light-dark) as seen in the micrograph. This result confirmed the results obtained from XRD and SEM/EDX analyses, which indicated that the minerals present in the ore are malachite, chalcopyrite, and silica mineral and also confirmed that the mineral of interest copper is present in the Anka-Brabra copper ore sample.

Sieve Analysis of Crude Sample of Anka-Brabra Copper Ore

The result of fractional sieve analysis of the crude sample of Anka-Brabra copper ore is presented in Table 4 while Figure 3 presents a plot of the percentage cumulative weight retained and passing against sieve size.

Table 4: Particle Size Analysis of Crude Sample of Anka-Brabra Copper Ore

Particle Size Range (µm)	Nominal Aperture Size (µm)	Weight Retained (g)	% Weight Retained	% Cumulative Weight Retained	% Cumulative Weight Passing	% CuO	% Cu
+1400	1400	5.32	5.33	5.33	94.67	32.04	25.59
-1400+1000	1000	11.20	11.23	16.57	83.43	32.91	26.29
-1000+710	710	10.60	10.63	27.20	72.80	49.32	39.39
-710+500	500	9,70	9.73	36.92	63.08	50.11	40.02
-500+355	355	9.20	9.23	46.15	53.85	53.32	42.59
-355+250	250	7.10	7.12	**53.27**	46.73	62.34	49.79
-250+180	180	15.40	15.44	68.71	31.29	58.22	46.50
-180+125	125	10.90	10.93	79.64	20.36	68.42	**54.65**
-125+90	90	14.80	14.84	94.48	5.52	63.62	50.81
-90+63	63	3.30	3.31	97.79	2.21	60.14	48.03
-63	pan	2.20	2.21	100.00	0.00	60.02	47.94

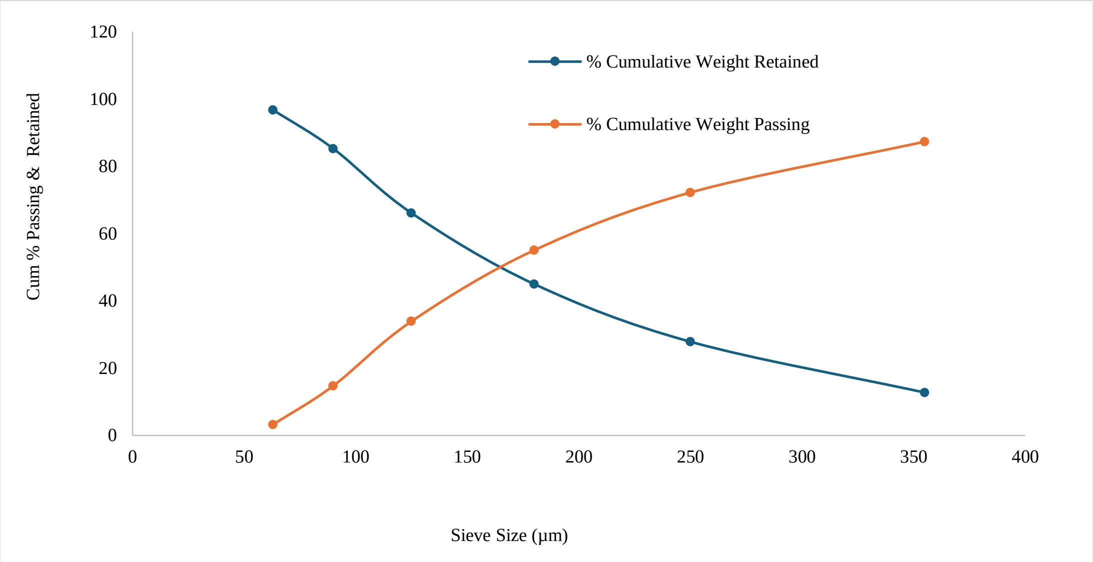


Figure 3: Direct plot of sieve size (µm) against % cumulative weight retained and passing of Anka-Brabra copper ore

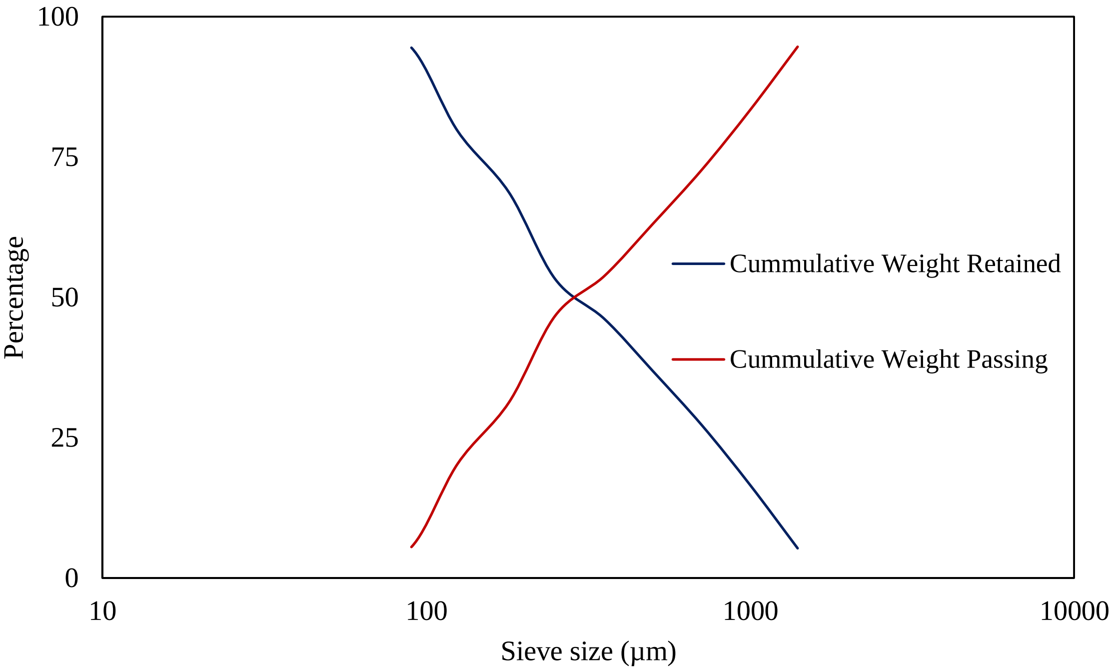


Figure 4: Plot of Log of Sieve Size (µm) against % Cumulative Weight Retained and Passing of Anka-Brabra Copper Ore

From Table 4, about 50% retention of the ore particles was achieved at 250 µm, which is synonymous with the point where the curves of % cumulative weight retained and passing intercept as represented in Figure 4. As deduced from the plot, the two curves are mirror-images of each other which symbolises a concurrent relationship between % cumulative weight retained and passing. Wills (2006) asserted that the size at which 50% retention or passing is achieved for a specific ore is termed the economic liberation size. Thus, it can be inferred that the economic liberation size of Anka-Brabra copper ore is 250 µm. However, this size is insufficient to describe the size at which the complete liberation of the copper mineral from associative minerals occurs (Umeliwu, 2023). However, it shows complete liberation below this point. A compositional analysis of the size fractions collected; the obtained result is contained in Table 5. It can be deduced that the optimum % Cu was obtained at a sieve size of 125 □m; this depicts the actual liberation size of the Anka-Brabra copper ore.

Table 5: Compositional Analysis of the Size Fractions Showing % Distribution of Copper Content

Nominal Aperture Size (µm)	Weight Retained (g)	% Weight Retained	% Cumulative Weight Retained	% Cumulative Weight Passing	Assay of Cu	Cu Content content	%Distribution
355	12.7	12.7	12.7	87.3	20.2	256.54	12.70127
250	15.11	15.11	27.81	72.19	20.2	305.222	15.11151
180	17.15	17.15	44.96	55.04	20.2	346.43	17.15172
125	21.13	21.13	66.09	33.91	20.2	426.826	20.25627
90	19.14	19.14	85.23	14.77	20.2	386.628	18.34856
63	11.52	11.52	96.75	3.25	20.2	232.704	11.04365
Pan	3.24	3.24	99.99	0.01	20.2	65.448	3.106026
						2019.798	

Work Index of Anka-Brabra Copper Ore

This parameter assesses the energy to be expended in crushing and grinding Anka-Brabra copper ore to its liberation size to prevent under-grinding or over-grinding and enhance the procurement of the appropriate grinding equipment (Alabi *et al.*, 2015). The evaluations of the necessary parameters needed to compute the work index of Anka-Brabra copper ore are presented below.

i. Feed to ball mill (Test ore and reference mineral)

The result obtained from fractional sieve size analysis of the reference ore (Anaka-Barba granite) is presented in Table 6.

a. Test ore analysis

Table 6: Particle Size Analysis of Test Ore (Anka-Brabra copper ore) prior to Milling

Particle Size Range (µm)	Nominal Aperture Size (µm)	Weight Retained (g)	% Weight Retained	% Cumulative Weight Retained	% Cumulative Weight Passing
+1400	1400	5.32	5.33	5.33	94.67
-1400+1000	1000	11.20	11.23	16.57	83.43
-1000+710	710	10.60	10.63	27.20	72.80
-710+500	500	9,70	9.73	36.92	63.08

-500+355	355	9.20	9.23	46.15	53.85
-355+250	250	7.10	7.12	53.27	46.73
-250+180	180	15.40	15.44	68.71	31.29
-180+125	125	10.90	10.93	79.64	20.36
-125+90	90	14.80	14.84	94.48	5.52
-90+63	63	3.30	3.31	97.79	2.21
-63	Pan	2.20	2.21	100.00	0.00

From Table 6

1000 µm = 83.43 %

80% Passing of test and reference ores were determined using the Gates-Gaudin-Schuhmann equation:

$$P(X) = 100\,\left[\frac{X}{K}\right]^{m} \tag{1}$$

P = percentage by weight of particles in the sample that are larger than a specific size (X)

X = This is the size of the particle, typically expressed in micrometres (µm).

K = Size modulus (µm), representing the size at which 100% of the particles would be larger (i. e P = 100%). A higher K value indicates a coarser particle size distribution.

m = Distribution modulus

$$X_{\mu m} = \left[\frac{\frac{80}{100}}{\frac{83.43}{100}}\right]^{2} x\ 1000$$

$$= \left(\frac{0.8}{0.8343}\right)^{2} x\ 1000$$

= 0.9195 x 1000

= 919.5µm at 80%

b. Reference mineral analysis

The result obtained from fractional sieve size analysis of the reference ore (Anaka-Barba granite) is presented in Table 7

Table 7: Particle Size Analysis of Reference Ore (Anka-Brabra graphite) before Milling

Particle Size Range (µm)	Nominal Aperture Size (µm)	Weight Retained (g)	% Weight Retained	% Cumulative Weight Retained	% Cumulative Weight Passing
+1400	1400	0.75	0.75	0.75	99.3
-1400+1000	1000	0.88	0.88	1.63	98.4
-1000+710	710	3.77	3.77	5.41	94.6
-710+500	500	45.28	45.33	50.73	49.3
-500+355	355	7.17	7.18	57.91	42.1

-355+250	250	16.35	16.37	74.28	25.7
-250+180	180	18.49	18.51	92.79	7.2
-180+125	125	2.01	2.01	94.80	5.2
-125+90	90	4.28	4.28	99.09	0.9
-90+63	63	0.5	0.50	99.59	0.4
-63	Pan	0.41	0.41	100.00	0.0

From Table 7,

If 710 µm = 94.60 %

$$X_{\mu m} = \left[\frac{\frac{80}{100}}{\frac{94.60}{100}}\right]^2 x\ 710$$

$$= \left(\frac{0.8}{0.9460}\right)^2 x\ 710$$

= 0.7152 x 710

= 507.8µm at 80%

ii. Products from the ball mill

a. Test Ore Analysis

The result obtained from fractional sieve size analysis of the test ore (Anka-Brabra copper ore) after milling is presented in Table 8.

Table 8: Particle Size Analysis of Test Ore (Anka-Brabra Copper Ore) after Milling

Particle Size Range (µm)	Nominal Aperture Size (µm)	Weight Retained (g)	% Weight Retained	% Cumulative Weight Retained	% Cumulative Weight Passing
+1400	1400	0.10	0.10	0.10	99.90
-1400+1000	1000	0.10	0.10	0.20	99.80
-1000+710	710	0.20	0.20	0.40	99.60
-710+500	500	32.00	32.16	32.56	67.40
-500+355	355	3.00	3.02	35.58	64.40
-355+250	250	19.40	19.50	55.07	44.90
-250+180	180	36.20	36.38	91.46	8.50
-180+125	125	1.10	1.11	92.56	7.40
-125+90	90	5.70	5.73	98.29	1.70
-90+63	63	0.90	0.90	99.20	0.80
-63	Pan	0.80	0.80	100.00	0.00

From Table 8;

If 710 µm = 99.60%

$$X_{\mu m} = \left[\frac{\frac{80}{100}}{\frac{99.60}{100}}\right]^2 x\ 710$$

$$= \left(\frac{0.8}{0.9960}\right)^2 x\ 710$$

= 0.6452 x 710

= 458.1 µm at 80%

b. Reference Ore Analysis

The result obtained from fractional sieve size analysis of the reference ore (Anka-Brabra granite) after milling is presented in Table 9.

Table 9: Particle Size Analysis of Reference Ore (Anka-Brabra Copper Ore) after Milling

Particle Size Range (µm)	Nominal Aperture Size (µm)	Weight Retained (g)	% Weight Retained	% Cumulative Weight Retained	% Cumulative Weight Passing
+1400	1400	0.1	0.10	0.10	99.90
-1400+1000	1000	0.01	0.01	0.11	99.89
-1000+710	710	0.02	0.02	0.13	99.87
-710+500	500	8.8	8.91	9.04	90.96
-500+355	355	5.4	5.47	14.51	85.49
-355+250	250	20.3	20.56	35.07	64.93
-250+180	180	53.29	53.96	89.03	10.97
-180+125	125	2.83	2.87	91.90	8.10
-125+90	90	6.7	6.78	98.68	1.32
-90+63	63	0.8	0.81	99.49	0.51
-63	pan	0.5	0.51	100	0

From Table 9;

If 355 µm = 85.49%

$$X_{\mu m} = \left[\frac{\frac{80}{100}}{\frac{85.49}{100}}\right]^2 x\ 355$$

$$= \left(\frac{0.8}{0.8549}\right)^2 x\ 355$$

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= 0.8757 x 355

= 310.9µm at 80%

iii. Work Index Evaluation

Using Bond's Equation:

$$W_t = W_{ir} \frac{\left[\frac{10}{\sqrt{P_r}} - \frac{10}{\sqrt{F_r}}\right]}{\frac{10}{\sqrt{P_t}} - \frac{10}{\sqrt{F_r}}} \qquad (2)$$

∴ $F_t = 919.5$ µm; $F_r = 507.8$ µm; $P_t = 458.1$ µm; $P_r = 310.9$ µm; $W_{ir} = 15.13$ kWh/ton (Alabi *et al.,* 2015)

$$W_t = 15.13 \times \frac{\left[\frac{10}{\sqrt{310.9}} - \frac{10}{\sqrt{507.8}}\right]}{\frac{10}{\sqrt{458.1}} - \frac{10}{\sqrt{919.5}}}$$

$$= 15.13 \times \frac{\left[\frac{10}{\sqrt{310.9}} - \frac{10}{\sqrt{507.8}}\right]}{\frac{10}{\sqrt{458.1}} - \frac{10}{\sqrt{919.5}}}$$

= 14.06 kWh/t

The work index of Anka-Brabra copper ore was calculated as 14.06 KWh/t– which when compared to the work index of other copper ores, the result obtained lies within 4–30 kWh/t (Weiss, 1985). The evaluated work index of Anka-Brabra copper ore depicts that about 14.06 kWh of energy will be expended to reduce one ton of the ore to 80% passing 100 µm (Nikolić & Trumić, 2021).

CONCLUSION

The chemical, mineralogical, and grindability studies of copper ore from the Anka-Brabra deposit has been investigated and the following conclusions were drawn.

i. That it comprises virtually pure Cu-carbonate hydroxide in the form of the mineral malachite ($Cu_{2}(CO_3)(OH)_2$) with traces of sodium aluminium silicate ($Na_2O.Al_2O_3.SiO_2$) and two forms of silica (SiO2), quartz and cristobalite according to XRF, XRD, petrological and SEM-EDS analysis.
ii. Liberation size of the Anka barba copper is 160, while about 50% retention of the ore particles was achieved at 250 µm, which is synonymous to the point where the curves of % cumulative weight retained and passed intercept.
iii. The work index of Anka-Brabra copper ore was calculated as 14.06 KWh/t, meaning that the evaluated work index is the energy to be expended to reduce one ton of the ore to 80% passing 100 µm.

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