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Efficacy of Mesh Size Variation on the Efficiency of Anka-Nassarawa (Zamfara State, Nigeria) Copper Ore Flotation

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Abstract This research investigated the influence of mesh size variation on the efficiency of froth flotation on Anka-Nassarawa copper ore, sourced from Zamfara State, Nigeria. Physical and chemical characterization was carried out, followed by sieve size analysis of the ore, leading to its crushing and grinding to liberation size and processing using froth flotation at sieves 250, 180, 125, 90 and 63 μm. Reagents used were pine oil as a frother, potassium ethyl xanthate as a collector, zinc sulphate – depressant, copper sulphate – activator and pH regulator was sodium hydroxide. Physical characterization showed that the ore has a metallic luster, dark bronze color with greenish stripes, and irregular breakages. Compositional analysis of the crude ore using X-ray fluorescence (XRF) revealed that the ore contains 12.271% CuO, 30.042% Fe_2O_3, 11.475% SiO_2, 32.128% Nb_2O_5, and 3.426% SO_2, along with trace amounts of other minerals, including NiO, WO_3, CaO, and ZrO_2. The liberation size of the ore was determined to be 125 μm, and the Bond work index was found to be 18.81 kWh/tonne and the energy used in comminution was 557.536 kWh. After froth flotation, the resulting froth and depressed samples were dewatered and analyzed using XRF. The highest copper grade of 43.82% CuO was obtained at a mesh size of 63 μm, confirming that this size is optimal for maximizing copper recovery from Anka-Nassarawa ore using froth flotation. The study demonstrates that the most efficient flotation results are achieved by grinding the ore to a 63 size lower than the determined liberation size.

Keywords Froth Flotation, Copper Ore, Mesh Size, Liberation Size, Bond Work Index, X-Ray fluorescence (XRF), Copper Recovery, Comminution

1. Introduction

Minerals are organic compounds that occur naturally, usually crystalline or non-crystalline, and are formed by geological processes. They can either be lodes or placers. Minerals in the form of lodes are consolidated minerals, e.g. hematite ore, such that there is a need to subject such minerals to successive comminution operations aimed at liberating the valuable ore from the gangue [1]. Metallic mineral deposits often referred to as ores, are rocks that contain economically valuable concentrations of metal. They are found in ore bodies and can be formed in different ways, for example, through hydrothermal, magmatic, metamorphic, sedimentary, and precipitation processes.

Ores are naturally occurring materials from which valuable minerals or metals can be profitably extracted. These deposits can vary widely in composition and mineral content [2–4].

Copper, one of the most important industrial metals, is essential for electrical wiring, plumbing, and various other applications due to its excellent electrical and thermal conductivity, corrosion resistance, and malleability [5,6]. Typically, copper is extracted from copper sulfide ores, which are mined and then processed to separate the valuable copper from the surrounding waste rock [7]. Copper was one of the early metals discovered by Neolithic man, including gold, silver, and meteoric iron [8]. Copper was first discovered in the region of Konya in southern Anatolia and is thought to be nearly nine millennia old (Turkey). Copper has been mined and used in the Old World since about then [9].

More than 200 minerals have detectable levels of copper, although only around 20 are useful as copper ores or semiprecious stones (turquoise and malachite) [9]. Copper is a good example of a chalcophilic element. As a result, its main minerals are sulfides, namely chalcopyrite, bornite, and chalcocite, with pyrite, galena, and sphalerite thrown in for good measure. Secondary minerals develop in two stages in sulfide ore deposits near the earth's surface. Copper oxides, basic salts (basic carbonates and basic sulfates), and silicates are formed in the oxidation zone by oxygen-containing water [2,10]. Other metallic elements frequently found in copper ores are iron, lead, zinc, antimony, and arsenic; less common are selenium, tellurium, bismuth, silver, and gold [12,13]. The selection of a particular production method depends essentially on the type of available raw materials, which is usually ore or concentrate, and on the conditions at the plant location [12,13].

The froth flotation method, developed in the early 20th century, remains a widely used technique for concentrating copper minerals. This process involves grinding the ore to a fine powder and mixing it with water to form a slurry. Reagents are added to this slurry to render the copper-bearing minerals hydrophobic, so they attach to air bubbles that are introduced into the mixture. These air bubbles rise to the surface, forming a froth that can be skimmed off, while the waste rock settles to the bottom. The efficiency of this separation process is significantly influenced by the size of the ground particles, commonly referred to as mesh size [7,11].

Earlier research by Purushothama *et al.* [15] on low-grade copper ore from the Ingaldhal area of Chitradurga District, Karnataka, focused on the mineralogical composition and flotation optimization. The study found that copper occurs primarily as chalcopyrite, accompanied by pyrite, pyrrhotite, covellite, and sphalerite, with feldspar, quartz, calcite, chlorite, and hornblende as gangue minerals. Liberation studies showed that optimal mineral liberation occurs below a 200-mesh size. Flotation experiments indicated that under optimal conditions, the copper content could be upgraded from 2.1% to 27.8%, with a total recovery of over 90%.

Olaniyan [16] investigated the impact of pH on the froth flotation of copper ore from Anka-Nassarawa, Nigeria. The study revealed that the ore contained chalcopyrite, siderite, quartz, and goethite, with significant copper-bearing minerals. By adjusting flotation parameters, particularly pH, the study achieved a copper concentrate grade of 15.9% at pH 10, with a copper recovery of 33.62%. This research suggested that Anka-Nassarawa copper ore could be a viable source for copper extraction and beneficiation for Nigeria's metallurgical industry.

Further studies by Asghari *et al.* [17] and Stirbavonic *et al.* [18] examined factors influencing copper recovery in flotation circuits. Asghari *et al.* found that copper loss to tailings was significantly affected by the particle size, with coarser particles (>74 μm) losing sulfide copper and finer particles (<9 μm) losing oxide copper. Adjusting the collector and sulfidization agent dosages improved recovery rates. Zoran et al. concluded that the optimal grinding size for flotation was 55–60% of grain size <74 μm, achieving a copper recovery of approximately 80% at a pH of 12, where better selectivity between copper minerals and pyrite was observed.

The study by Taofeek and Amos [19] investigated the bulk density, compressional strength, hardness, particle size distribution, and chemical composition of ore from Akiri using standard methods and Energy Dispersive X-ray Fluorescence Spectrometry (ED-XRFS). The results indicated a bulk density of 3.58 g/cm^3, compressional strength of 1.24%, and hardness of 96.0 N. The particle size analysis revealed oversize fractions above 250 μm. The chemical composition analysis showed that the ore contains various minerals, including 63.52% Fe_2O_3, 11.25% SO_3, 7.62% CuO, 4.30% MoO_2, 3.18% SiO_2, among others. The results highlighted a significant concentration of Cu (6.10%) compared to other elements, except Fe, which showed a higher concentration (35%). This suggests that the Akiri ore has potential for processing valuable minerals.

Previous studies have shown that the particle size of the ore significantly impacts the froth flotation process. However, the optimal mesh size for maximum copper recovery from Anka-Nasarawa copper ore has not been comprehensively studied. Effective and efficient extraction of copper from its ores is vital for the economic sustainability of mining operations. The froth flotation process, while effective, is highly sensitive to the physical characteristics of the ore, particularly the particle size. In the context of Anka-Nasarawa copper ore, identifying the most efficient mesh size for froth flotation is crucial.

This study uniquely contributes to the optimization of copper ore beneficiation from the Anka-Nassarawa region using froth flotation. While copper recovery via flotation has been well-documented for various ores, there has been no comprehensive investigation on the ideal mesh size for this ore. This research aims to fill this gap, with potential

implications for improving the economic viability of copper extraction in this region.

2. Materials and Methods

2.1. Materials

Materials used in the course of this research are ten kilograms (10 Kg) of copper ore samples sourced from Anka-Nassarawa, Zamfara State, Nigeria and one kilogram (1 kg) Quartz Sample used as reference ore for grindability test sourced from overburden material to copper ore from the same location. Froth flotation reagents used are Sodium ethyl xanthate (collector), Methyl isobutyl carbinol (frother), Lime (pH modifier) and Sodium cyanide (depressant). Likewise, the equipment used is the Denver jaw crusher, ball mill for grinding the ore, set of sieves for required particle size preparation, Denver froth flotation machine including flotation cells for processing, and X-ray fluorescence (XRF) analyzer for crude ore and products compositional analysis.

2.2. Methods

2.2.1. Sample Preparation

Crushing and grinding of the sourced copper ore sample were carried out using a Denver jaw crusher model C5X, 0.25 – 1.0 TPH to reduce the size of the rocks from boulders. The crushed ore was then ground in a laboratory size ball mill, model 50 - HP, capacity 0.2 Kg/hr to achieve the desired particle size distribution. The ground ore was sieved into different mesh sizes: 90, 63, 125, 180, and 250μm. Each size fraction was collected for subsequent flotation tests. These mesh sizes (90, 63, 125, 180, and 250 μm) were selected based on the expected particle size distribution for efficient liberation of copper minerals, as suggested by preliminary sieve analysis and previous research [15]. Also, these sizes were chosen to provide a wide range of particle sizes, allowing for a comprehensive evaluation of flotation efficiency across different levels of mineral liberation.

2.2.2. Chemical and Mineralogical Analysis

Characterization was performed using Energy Dispersive X-ray Fluorescence Spectrometry (ED-XRFS) to analyze the elemental composition and mineralogical properties determined by the use of an X-ray diffractometer (XRD) at the analytical laboratory of the National Steel and Raw Material Exploration Agency, Kaduna – a Federal Government own research centre in Nigeria. This was followed by the determination of ore properties. A grindability test using a modified Bond's method was performed to determine the work index of the ore, with samples ground for different durations and subjected to sieve analysis.

2.2.3. Froth Flotation

Ore pulp conditioning was done by charging the ore into 1500 mls capacity denver froth flotation cell, model d12. Five hundred grams (500 gms.) of the sieved copper ore were charged into the cell, and it was mixed with 1000 mls of distilled water to form a slurry at a ratio of 1:2. Potential hydrogen level (pH) was tested and adjusted to 10 using Lime (1.0 kg/t). Reagents were added to the slurry in the following order and amounts, sodium ethyl xanthate (0.05 kg/t) as a collector to enhance the hydrophobicity of copper minerals. Sodium cyanide (0.01 kg/t) is used to depress unwanted sulfide minerals and methyl isobutyl carbinol (0.01 kg/t) as a frother to stabilize the froth at an impeller of 1500 rpm. Air was bubbled through the pulp, generating froth at the surface. The hydrophobic copper minerals attached to the air bubbles and rose to the surface, forming a froth layer. The froth containing the copper concentrate was skimmed off the surface of the flotation cell. The remaining slurry contained the gangue minerals (depressed sample). These samples collected as froth and depressed were allowed to settle for 24 hours, decanted, filtered and dried in a laboratory drying oven, model B2B at 105°C. The dried samples were analyzed using an X-ray fluorescence (XRF) analyzer to determine the copper content. This was repeated for the samples of sieves 90μm, 63μm, 125μm, 180μm, and 250μm respectively.

2.3. Results and Discussion

The results obtained in the course of this research are presented in Tables 1 – 7 and Figures 1 to 4 respectively.

2.3.1. Characterization of Anka-Nassarawa Copper Ore

The result of the chemical analysis of the Anka-Nassarawa copper ore using Energy Dispersive X-ray Fluorescence (ED-XRF) is shown in Table 1.

Table 1 revealed that the ore primarily contains 12.271% CuO, 20.042% Fe_2O_3, 51.475% SiO_2, 2.128% Nb_2O_5, and 3.426% SO_2. Additionally, it includes trace amounts of minerals like NiO (0.251%), WO_3 (0.07%), CaO (0.66%), Cl (0.736%), ZrO_2 (0.706%), and PbO (0.274%). This proves that the ore in question is a copper ore of 12.271% CuO grade and contains some other associated minerals such as silica, iron ore as major impurities, and others as minor impurities. This shows the need for processing the ore to improve the grade of copper and reduce the grade of impurities; for the copper to be useful industrially.

Table 1. Chemical Composition of Crude Anka-Nassarawa Copper Ore

Compd.	SiO_2	Fe_2O_3	NiO	CuO	Nb_2O_5	WO_3	SO_2	CaO	TiO_2	ZnO	Cl	ZrO_2	PbO	Ce_2O_5
% Conc.	51.475	20.042	0.251	12.271	2.128	0.07	3.426	0.66	2.067	0.155	0.736	0.706	0.274	0.042

2.3.2. Sieve Analysis

Sieve analysis was conducted to determine the particle size distribution of the copper ore in various sieve sizes to confirm at which sieve size the mineral of interest which is copper is most populated, hence known as the liberation size of the mineral of interest from its ore after the ore was crushed and ground to this liberation size. The crushed ore (test ore) was charged into the ball mill and the product from the ball mill was both charged into an array of sieves ranging from 1000µm to 63µm on an automated Endecott sieve shaker and was shocked for 15 minutes after which each of the sieves was carefully weighed and weight recorded and plotted as in Tables 2–5 and Figures 1-4, with percentages cumulative weight retained and passing calculated for each size. This was repeated for the reference ore which happened to be an over burden soured from the Anka – Nassarawa copper ore deposit.

Table 2. Sieve Analysis of the Anka-Nassarawa Zamfara Copper Ore Charge into the ball mill. (Test Ore)

Sieve Sizes(µm)	Sieve range	Weight (g)	% Wt. Retained	% Cumulative Retained	% Cumulative Passing
1000	1000	0.28	0.0569	0.0569	99.9431
710	-1000 +710	0.03	0.00686	0.06376	99.93624
500	-710 +500	4.18	0.84399	0.90775	99.09225
355	-500 +355	9.25	1.86589	2.77364	97.22636
250	-355 +250	39.50	7.96743	10.74107	89.25893
180	-250 +180	28.62	5.77376	16.51483	83.48517
125	-180 +125	80.50	16.2372	32.75203	67.24797
90	-125 +90	80.65	16.2693	49.02133	50.97867
63	-90 +63	178.78	36.0624	85.08373	14.91627
pan	-63 +pan	73.95	14.9162	100	0
		Total = 495.743	100		

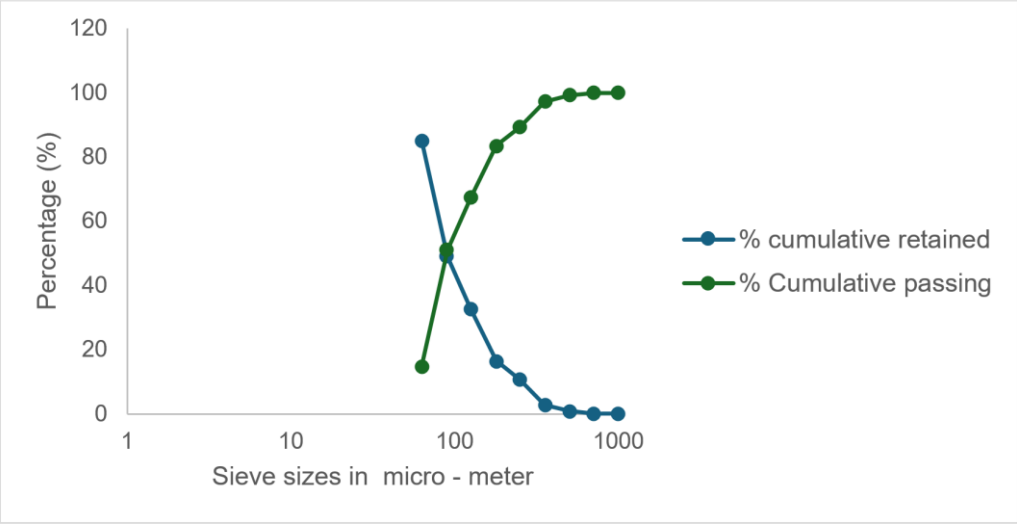

Figure 1. Plot of Log-Log of Cumulative % weight Retained and Passing against Sieve size (µm) of the Anka-Nassarawa Zamfara copper ore charge into the ball mill

Table 3. Sieve Analysis of the Anka-Nassarawa Zamfara Copper Ore Product from the ball mill. (Test Ore)

Sieve Sizes(µm)	Sieve range	Weight (g)	% Wt. Retained	% Cumulative Retained	% Cumulative Passing
1000	1000	0.27	0.00558	0.00558	99.994
710	-1000 +710	0.007	0.001448	0.007028	99.9929
500	-710 +500	0.748	0.15471	0.161738	99.83826
355	-500 +355	0.393	0.08128	0.243018	99.75698
250	-355 +250	1.09	0.22544	0.468458	99.53154
180	-250 +180	2.485	0.51397	0.982428	99.01757
125	-180 +125	18.525	3.8315	4.813928	95.18607
90	-125 +90	92.077	19.04416	23.858088	76.14191
63	-90 +63	297	61.42811	85.286198	14.7138
pan	+pan	71.14	14.71379	100	0.0
		Total = 483.492	100		

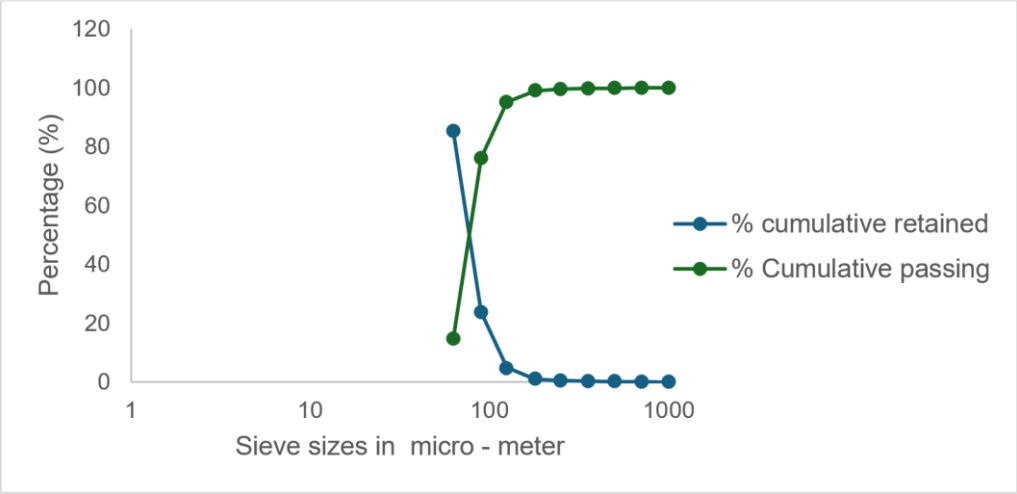

Figure 2. Plot of Log-Log of cumulative % weight Retained and Passing against Sieve size (µm) of the Anka-Nassarawa Zamfara copper ore Product from the ball mill

Table 4. Sieve Analysis of Quartz Feed or Charge into the ball mill. (Reference Ore)

Sieve Sizes(µm)	Sieve range	Weight (g)	%Wt. Retained	% Cumulative Retained	% Cumulative Passing
1000	1000	21.50	4.30	4.30	95.70
710	-1000 +710	36.30	7.30	11.60	88.40
500	-710 +500	23.75	4.80	16.40	83.60
355	-500 +355	30.75	6.21	22.61	77.39
250	-355 +250	30.05	6.09	28.70	71.30
180	-250 +180	21.75	4.40	33.10	66.90
125	-180 +125	92.50	18.60	51.70	48.30
90	-125 +90	64.75	13.00	64.70	35.30
63	-90 +63	110.20	22.20	86.90	13.10
pan	+pan	65.00	13.10	100.00	0
		Total = 483.492	100.0		

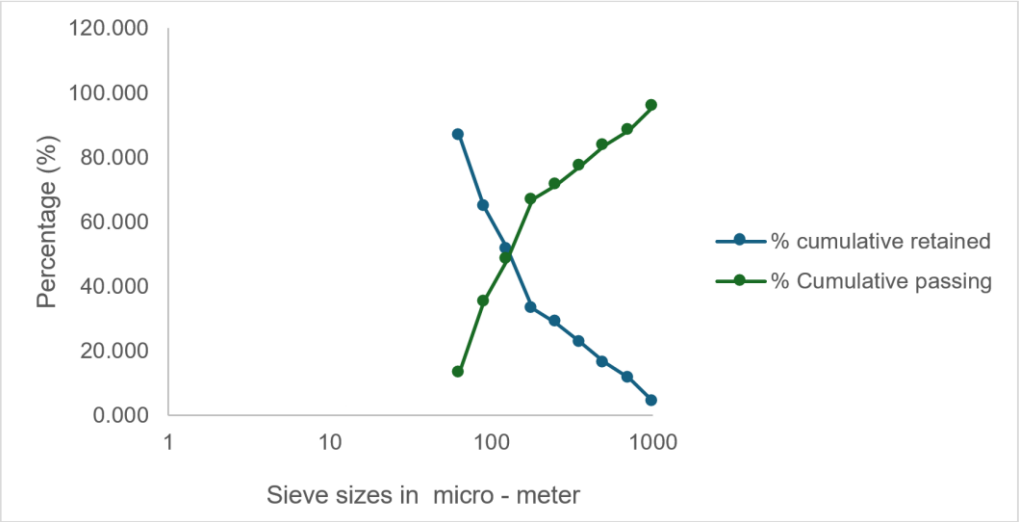

Figure 3. Plot of Log-Log of Cumulative% Weight Retained and Passing against sieve sizes (µm) of the Quartz (Reference Ore) Feed or charge into the Ball Mill

Table 5. Sieve Analysis of Quartz Product from the ball mill. (Reference Ore)

Sieve Sizes(µm)	Sieve Range	Weight (g)	% Wt. Retain	% Cumulative Retained	% Cumulative Passing
1000	1000	0.00	0.00	0.000	0.000
710	-1000 +710	0.00	0.00	0.000	0.000
500	-710 +500	1.20	0.25	0.245	99.755
355	-500 +355	6.50	1.33	1.570	98.430
250	-355 +250	14.50	2.96	4.530	95.470
180	-250 +180	9.60	1.96	6.489	93.511
125	-180 +125	169.50	34.59	41.074	58.926
90	-125 +90	98.70	20.14	61.213	38.787
63	-90 +63	112.60	22.98	84.188	15.812
pan	+pan	77.50	15.81	100.000	0.000
		Total = 490.1	100.0		

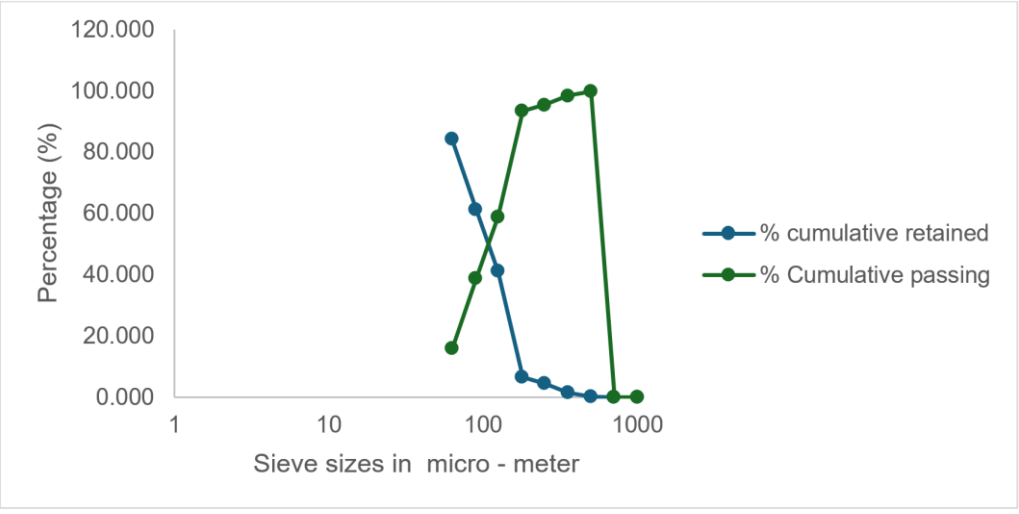

Figure 4. Plot of Log-Log of Cumulative% Weight Retained and Passing against sieve sizes (µm) of the Granite (Reference Ore) Product from the Ball Mill

Calculate the work index using modified bond's method applying equations i and ii using values from Tables 2–5.

$$Sieve_2 = \left(\frac{Percentage\ \ Passing\ \ Sieve_2}{Percentage\ \ Passing\ \ Sieve_1}\right)^2 \times Sieve\ \ Sieve_1 (1)$$

$$= \left(\frac{\frac{80}{100}}{\frac{83.49}{100}}\right)^2 \times 180 = 165.27\ \mu m$$

$$Ft = \left(\frac{0.8}{0.8349}\right)^2 \times 180 =$$

$$165.27\mu m\ \ at\ \ 80\%\ \ passing \text{ (Test Ore)}$$

Equation i repeated for for For 90% µm = 76.142%

$$Sieve_2 = \left(\frac{Percentage\ \ Passing\ \ Sieve_2}{Percentage\ \ Passing\ \ Sieve_1}\right)^2 \times Sieve\ \ Sieve_1$$

$$Pt = \left(\frac{80/100}{76.142/100}\right)^2 \times 90 = 99.35\mu m$$

Pt = 99.35µm at 80% passing

Furthermore, calculations involving the reference Ore use equation i and values from Tables 4 and 5 respectively.

$$Fr = \left(\frac{80/100}{66.90/100}\right)^2 \times 180 = 257.395\mu m, \text{ and}$$

Pr = 336.79 $\mu m\ \ at$ 80% passing

Now to calculate, work index of the Ore sample under study using equation ii

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

With work index of Quartz to be 15.0 kWh/ton
Wir = 15.0 kWh/ton, Ft = 165.27, Pt = 99.35, Fr = 257.395, Pr = 336.79, W_{it} = ?

Substituting all values at equation ii.

$$W_{it} = \left(\frac{\left(\frac{10}{336.79} - \frac{10}{257.395}\right)}{\left(\frac{10}{99.35} - \frac{10}{165.27}\right)}\right) \times 15.0$$

$$Wit = 18.81 KWh/Tonne \text{ for test ore.}$$

Hence, energy used in grinding the sourced ore was calculated using equation iii when Wit = 18.81 kWh/t, P_t = 99.35 µm, F_t =165.27, W_{Energy} = ?

$$W_{Energy} = 10\ W_{it}\ \left(\frac{1}{\sqrt{Pt}} - \frac{1}{\sqrt{Ft}}\right),$$

$$= 10\ (18.81)\left(\frac{1}{\sqrt{99.35}} - \frac{1}{\sqrt{165.27}}\right)$$

$$W_{Energy} = 4.326 \text{ kWh}$$

This proves that the energy used for grinding the test ore to liberation size of 125 µm is 4.326 kWh., with a special note that most of the energy was converted to other forms such as waste through light, sound and only 1% calculated energy was actually used for the comminution process.

2.3.3. Froth Flotation Results

Froth flotation was conducted on samples of different mesh sizes (63µm, 90µm, 125µm, 180 µm, and 250 µm), Tables 6 and 7 respectively.

Table 6 revealed that the weight of products in froth increases from 111.0 – 213 grams and that of depressed decreases from 389 – 287 grams as the sieve sizes decrease from the charge of 500 grams to each sieve at different sizes. Copper grade in the froth increases through the sieve sizes from 37.52% to 43.82 CuO and the grade of copper loss to depressed is in the range of 17.17 – 19.94% CuO from the start up charge grade of 12.271% CuO. This shows clearly that processing has taken place [12].

Table 6. Weight of Froth and Depressed and their Assay of Copper in crude, froth and depressed processed Anka-Nassarawa Zamfara Copper Ore

Sample (µm)	Wt of crude (g)	Wt. % CuO in Crude	Wt of froth (g)	Wt. % CuO in Froth	Wt of depressed (g)	Wt. % CuO in depressed
250	500	12.271	111	42.2	389	18.91
180	500	12.271	112	37.52	388	19.94
125	500	12.271	184	38.29	316	17.17
90	500	12.271	213	38.11	287	19.46
63	500	12.271	138	43.82	362	18.11

Table 7. Metallurgical Accounting Table of Anka-Nassarawa Zamfara Copper Ore

Sample (µm)	Wt of Crude (F)	Wt. % CuO Crude (f)	Wt of froth (C)	Wt. % CuO froth (c)	Recovery Cc/Ff x 100	Enrichment Ratio c/f	Concentration Ratio F/C
250	500	12.271	111	42.2	76.35	3.44	4.50
180	500	12.271	112	27.52	68.49	2.24	4.46
125	500	12.271	184	28.29	84.84	2.31	2.72
90	500	12.271	213	28.11	97.59	2.29	2.35
63	500	12.271	138	43.82	98.56	3.57	3.62

This revealed the metallurgical accounting parameters calculated using the values obtained during the research and input to complete Table 7 to justify the results obtained during the froth flotation process of Anka – Nassarawa copper ore.

From Table 7, the recovery range of 68.49 to 98.56% was obtained from sieve sizes of 180 μm to 63 μm, a concentration ratio of 2.35 to 4.50 at 90 μm to 250 μm and an enrichment ratio of 2.24 to 3.56 at 180 μm to 63 μm with the highest grade 43.82% experienced at a recovery of 98.56%, a concentration ratio of 3.62 and an enrichment ratio of 3.57 all obtained at a sieve size of 63μm mesh size, hence regarded as the best processing route [10]. This shows an increase in the grade of copper in all the products compared to its grade in crude which contains 12.271% CuO; hence, success in beneficiation using froth flotation process was recorded. From this result, it shows that the recovery rates of this process were optimized at 63μm sieve size as it achieved the highest grade, recovery, concentration ratio and enrichment ratio as in Table 7 and finally confirmed that 63μm hosts the optimal copper grade known as metallurgical standard towards copper extraction.

Furthermore, these results indicate that the particle size of the ore has a pronounced effect on the efficiency of the froth flotation process. The highest copper grade, 43.82% CuO, was achieved at a mesh size of 63μm. This suggests that 63μm is the optimum particle size for maximizing copper recovery from the Anka-Nassarawa ore using froth flotation.

The efficiency of the flotation process decreases for larger mesh sizes than 63μm. For instance, at 90μm and 125μm, the copper grades dropped to 37.885% and 38.109%, respectively. Similarly, for coarser particles, the copper grades were 29.461% at 180μm and 28.293% at 250μm. This decline in copper grade recovery at larger sizes other than 63μm can be attributed to several factors. At larger particle sizes (Under grind), incomplete liberation of the copper minerals from the gangue may occur, reducing the effectiveness of the flotation process [13,14]. On the other hand, at finer particle sizes (over grind), the increased surface area and potential for slime formation can lead to poor froth stability and decreased flotation efficiency.

The findings of the result show the importance of optimizing particle size in the froth flotation process to enhance copper recovery. The determination that under the set of experiments performed, and 63μm demonstrated the best performance in terms of copper recovery, which provides valuable insight for improving the economic viability of copper ore mined from Anka-Nassarawa for copper metal extraction. Further investigation using statistical methods (e.g., Design of Experiments) may reveal whether finer mesh sizes could yield even better results.

3. Conclusions

The influence of sieve size variation study on the efficiency of froth flotation of copper was carried out and the following conclusions were made:

i. Anka-Nassarawa copper ore was found to be a metallic lustre, dark brass with a greenish stripe and it has irregular breakages with liberation size at 125μm, with 12.271% CuO;
ii. the work bond index of Anka-Nassarawa copper ore was determined to be 18.81kWh/tonne., and energy expended on comminution to be 4.326 kWh;
iii. the optimum grade of 43.83% CuO was produced at 63 μm;
iv. the optimum recovery of 98.56% was also attained at 63 μm which shows an optimized process that produces the best grade of copper at 63 μm mesh size as against the assumed liberation size of 125 μm.

The research findings suggest that a sieve size of 63 μm produced the best results in terms of copper recovery under the conditions tested, outperforming the liberation size of 125 μm.

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