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Effect of Particle Size and Process Variables on Shaking Table Concentration of Makarfi Ilmenite Ore

A.M. Obi, I. Isa, and M.N.S. Usaini
Department of Mineral and Petroleum Resources Engineering, Kaduna, Kaduna Polytechnic
Corresponding Author: isaibrahim@kadunapolytechnic.edu.ng

ABSTRACT
Ilmenite ($FeTiO_3$) is a titanium-bearing mineral essential for the production of titanium dioxide (TiO_2), widely used in pigments, aerospace, medical devices, and welding electrodes. With increasing global demand for titanium products, optimizing ilmenite ore concentration is crucial to enhance its economic value. Nigeria has substantial yet underexplored ilmenite deposits, particularly in Kaduna, Nasarawa, and Plateau States, with the Makarfi region in Kaduna State believed to host large deposits that remain largely uninvestigated. This study focused on optimizing the concentration of Makarfi-Kaduna ilmenite ore using shaking table separation, a gravity-based method exploiting differences in specific gravity between ilmenite and gangue minerals such as quartz and feldspar. Ore samples were collected, homogenized, and characterized using X-ray fluorescence (XRF) and X-ray diffraction (XRD), and shaking table experiments were conducted to evaluate the effects of particle size, feed rate, and water flow on recovery and concentrate grade. Results indicated the presence of goethite (44%), ilmenite (38%), quartz (10%), and cuprite (8.1%), with significant iron (20.21%) and titanium (20.31%) contents. Recovery was lower for finer particles, while the 212 µm fraction produced the highest titanium content (36.71%) in the concentrate. The study demonstrates that optimizing particle size and separation parameters can significantly improve ilmenite recovery and concentrate quality, providing insights for sustainable beneficiation of Makarfi-Kaduna ilmenite and reducing Nigeria's reliance on imported titanium feedstock.

Keywords: *Ilmenite, Makarfi-Kaduna, shaking table, beneficiation, titanium dioxide, gangue minerals, ore optimization, Nigeria*

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I. INTRODUCTION

Ilmenite ($FeTiO_3$) is a vital titanium-bearing mineral primarily used in producing titanium dioxide (TiO_2), which has numerous applications in pigments, aerospace materials, medical devices, and welding electrodes. With the global demand for titanium products rising, optimizing ilmenite ore concentration is crucial to improve both quality and economic value. Nigeria, endowed with significant mineral resources, possesses substantial yet underexplored ilmenite deposits, particularly in Kaduna, Nasarawa, and Plateau States. The Makarfi region in Kaduna State is believed to host large ilmenite-bearing deposits; however, detailed geological and mineralogical data are limited (Abdel-Khalek et al., 2020). Concentration processes enhance ore value by removing unwanted gangue materials, and gravity separation using shaking tables is widely employed for this purpose. This method exploits differences in mineral specific gravity, enabling separation of valuable ilmenite from lighter gangue such as quartz and feldspar, but its efficiency depends on factors including feed particle size, feed rate, table tilt angle, and water flow rate (Elmenshawy et al., 2020).

The effectiveness of shaking table separation is influenced by the physical and chemical properties of the ore, and different ilmenite deposits respond differently under varying conditions, necessitating site-specific optimization (Hassan et al., 2020). Improper control of process parameters can result in low recovery rates and poor concentrate grades, as high feed rates, incorrect tilt angles, or overly fine particles can reduce mineral stratification and cause losses (Mutelet et al., 2020). In Makarfi-Kaduna, the presence of silicate gangue minerals such as quartz and feldspar complicates concentration, as these impurities often have similar particle sizes and specific gravities to ilmenite, reducing separation efficiency (Singh & Rao, 2018; Teng et al., 2016).

This study aims to investigate the process variables affecting shaking table concentration of Makarfi-Kaduna ilmenite ore, including mineralogical and chemical characterization, the effect of feed particle size on recovery and concentrate grade, and optimization of operational conditions. The findings will provide critical data for improving beneficiation strategies and enhancing the ore's economic value, offering insights to both academic researchers and industrial stakeholders. Optimizing the concentration process can enhance ilmenite recovery and concentrate quality, reduce material losses, improve processing efficiency, and promote sustainable mining practices (Tang, 2016; Youssef et al., 2020). Additionally, local production of high-quality titanium feedstock could support Nigerian industries, reduce dependence on imports, and contribute to economic diversification and job creation (Helal et al., 2020).

Mineral beneficiation contributes significantly to economic development by adding value to raw ores, promoting local industries, and creating employment opportunities. In Nigeria, the underutilization of ilmenite limits industrial growth and foreign exchange earnings. Despite Makarfi's known ilmenite deposits, systematic beneficiation remains limited, resulting in resource loss and missed economic opportunities. Furthermore, there is scant research on the application of modern recovery techniques, such as magnetic separation, to these deposits.

This study aims to investigate the application of magnetic separation for the recovery of ilmenite from Makarfi, Kaduna State. The specific objectives are: (i) to carry out mineralogical and chemical analyses of Makarfi ilmenite ore, (ii) to test magnetic separation techniques for ore recovery, and (iii) to analyze the resultant products. The study focuses on laboratory-scale beneficiation, including ore sampling, mineralogical and magnetic characterization, and separation using magnetic equipment. It does not extend to downstream titanium extraction or alloy production.

The significance of this research lies in contributing to the knowledge base on ilmenite beneficiation in Nigeria, providing empirical data for future geological and metallurgical studies, and supporting local beneficiation initiatives. Successful application of magnetic separation for Makarfi ilmenite could encourage investment in small- to medium-scale mineral processing, improve domestic resource utilization, and guide policymakers and mining operators toward environmentally sustainable and economically viable beneficiation practices (Wills & Finch, 2016; Liu et al., 2011; Oyinloye & Jegede, 2014; Tripathy et al., 2013; Chen et al., 2012).

Figure 1: Map of Kaduna Indicating the Study Area

II. METHODS

The ilmenite ore samples for this study were collected from the Makarfi Local Government Area in Kaduna State using the grab sampling method to ensure representativeness of the outcrop for qualitative analysis and grade assessment, with geographic coordinates recorded as 11°13′15.0″ N and 7°56′00.0″ E.

Figure 1: Goggle Earth Map Showing the Coordinates of the Study Area

The samples were homogenized using the coning and quartering method to ensure uniformity and subsequently dried to remove moisture that could interfere with particle characterization. Chemical analysis was performed using X-ray fluorescence (XRF) with the Genius IF Xenemetrix XRF equipment, enabling identification and quantification of major and trace elements including Fe, Ti, Si, Al, Ca, Mg, Mn, and P, thereby providing critical information on ore grade and suitability for concentration. Mineralogical characterization was conducted via X-ray diffraction (XRD) on powdered samples to identify crystalline mineral phases, revealing the presence of ilmenite, hematite, and silicate impurities. Sieve analysis was carried out to determine particle size distribution using standard sieves with mesh openings of 63 μm, 150 μm, and 212 μm, classifying the ore into fine, medium, and coarse fractions. These particle size classifications were essential for assessing the impact of particle size on the efficiency of shaking table concentration.

III. RESULTS AND DISCUSSION

The mineralogical analysis of Makarfi ilmenite ore presented in Figure 2 indicates that goethite (44%) is the dominant mineral, followed by ilmenite (38%), quartz (10%), and cuprite (8.1%). The high abundance of goethite suggests significant oxidation of the ore, which may complicate beneficiation due to its iron content, necessitating methods such as magnetic separation or acid leaching for its removal. Ilmenite, the primary titanium-bearing mineral, constitutes 38% of the ore, confirming its economic potential for TiO_2 production.

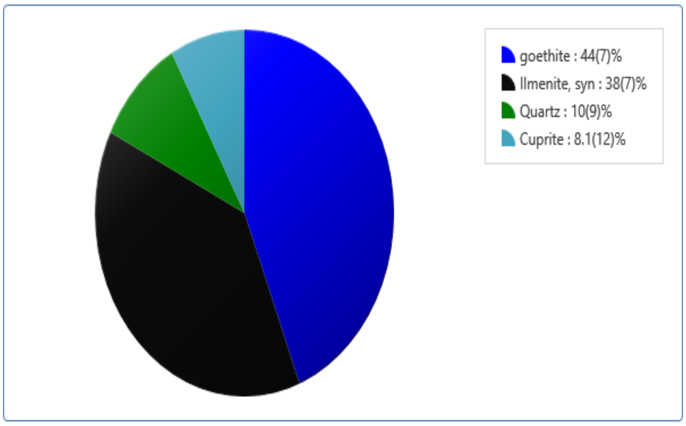

Figure 2: Mineralogical Analysis of Makarfi Ilmenite Ore

Quartz, although less abundant, is an inert gangue mineral that requires separation to improve concentrate grade, while cuprite, a copper oxide, may contaminate the ilmenite concentrate, requiring additional processing steps. Overall, while the ore exhibits promising titanium content, effective removal of goethite, quartz, and cuprite is critical to optimize the ore for industrial applications.

Table 1: Mineralogical Analysis of Makarfi Ilmenite Ore (EDX/SEM Analysis)

Element No.	Symbol	Element	Atomic Conc. (%)	Weight Conc. (%)
26	Fe	Iron	28.83	39.18
22	Ti	Titanium	24.20	28.19
14	Si	Silicon	40.73	27.83
13	Al	Aluminium	4.59	3.01
25	Mn	Manganese	0.43	0.58
19	K	Potassium	0.56	0.54
23	V	Vanadium	0.26	0.32
16	S	Sulfur	0.22	0.17
20	Ca	Calcium	0.17	0.17
11	Na	Sodium	0.00	0.00
12	Mg	Magnesium	0.00	0.00
15	P	Phosphorus	0.00	0.00
17	Cl	Chlorine	0.00	0.00

The chemical analysis of the 063 µm particle size fraction presented in Table 2 reveals iron (Fe) and titanium (Ti) contents of 20.21% and 20.31%, respectively, confirming the ore's potential for TiO_2 production. The significant silicon (Si, 11.54%) and aluminium (Al, 3.10%) indicate the presence of silicate gangue minerals, such as quartz and feldspar, which must be removed to enhance concentrate quality. Minor elements including manganese (Mn), phosphorus (P), potassium (K), and calcium (Ca) further complicate separation but occur at low concentrations, whereas trace elements like cobalt, copper, and tantalum have negligible effects on beneficiation.

Table 2: Chemical Analysis of 063 µm Particle Size

Element	Wt%	Element	Wt%	Element	Wt%
Si	11.54	Co	0.08	Pb	0.09
V	0.44	Cu	0.03	Rb	0.01
Mn	0.50	Nb	0.00	Cs	0.54
Fe	20.21	W	0.02	Sr	0.00
P	0.25	S	0.11	Al	3.10
Ca	1.23	K	0.59	Ti	20.31
Ba	0.02	Ta	0.04	Zn	0.01
Cl	0.99	Zr	0.00		

Similarly, the 150 µm fraction presented in Table 3 shows Fe and Ti contents of 17.23% and 16.14%, respectively, while Si increases to 16.65%, reflecting a higher proportion of gangue minerals in coarser particles. Minor impurities such as Al, Ca, and Mg further highlight the need for efficient beneficiation to improve concentrate purity. The 212 µm fraction presented in Table 4 exhibits Fe and Ti contents of 17.88% and 17.01%, with Si at 16.48% and Al at 3.10%, consistent with trends observed in coarser fractions, indicating that particle size influences the distribution of valuable minerals and gangue, and that efficient separation strategies are essential.

Table 3: Chemical Analysis of 150 µm Particle Size

Element	Wt%	Element	Wt%	Element	Wt%
Si	16.65	Nb	0.19	Ti	16.14
V	0.44	W	0.01	Zn	0.02
Mn	0.39	P	0.01	Cl	0.50
Fe	17.23	S	0.20	Zr	0.03
Co	0.07	Ca	0.78	Pb	0.14
Cu	0.04	Mg	0.75	Rb	0.06
Nb	0.19	K	0.73	Cs	0.55
W	0.01	Al	3.12	Sr	0.02

Table 4: Chemical Analysis of 212 µm Particle Size

Element	Wt%	Element	Wt%	Element	Wt%
Si	16.48	Nb	0.09	Pb	0.08
V	0.40	W	0.01	Rb	0.04
Mn	0.45	P	0.00	Cs	0.79
Fe	17.88	S	0.05	Sr	0.03
Co	0.05	Ca	0.44	Al	3.10
Cu	0.07	K	0.80	Ti	17.01
Nb	0.09	Ta	0.06	Zn	0.01
W	0.01	Cl	0.44	Zr	0.09

Shaking table concentration presented in Table 5 demonstrated that particle size significantly affects iron and titanium recovery. For Fe_2O_3, concentrations in tailings decrease across all fractions, indicating effective removal of iron-rich gangue; however, larger particles (212 µm) retain higher iron in tailings (14.76%), suggesting less efficient separation. Titanium recovery is highest in the 212 µm fraction (36.71%), while finer particles (063 µm) show greater losses (14.44%) in the tailings. These results emphasize that coarser fractions are more effectively concentrated, and optimizing particle size and separation parameters is critical for improving recovery and concentrate quality.

Table 5. Shaking Table Analysis (XRF Results)

Chemical Formula	Head Sample (%)	063 µm Conc. (%)	063 µm Tailings (%)	150 µm Conc. (%)	150 µm Tailings (%)	212 µm Conc. (%)	212 µm Tailings (%)
Fe_2O_3	33.28	28.90	16.54	31.54	24.63	33.07	14.76
TiO_2	33.13	33.89	14.44	32.83	26.93	34.73	14.81

IV. CONCLUSION AND RECOMMENDATION

The chemical analysis of Makarfi ilmenite ore across different particle sizes (Head Sample, 063 µm, 150 µm, and 212 µm) demonstrates significant trends in the beneficiation process. Iron oxide (Fe_2O_3) in the head sample is 33.28%, decreasing in the tailings, which indicates effective removal of iron-bearing gangue minerals. However, the 212 µm fraction retains notable iron in the tailings (14.76%), suggesting that coarser particles are less efficiently separated. Titanium dioxide (TiO_2) concentration in the head sample is 33.13%, with higher enrichment observed in the concentrates; the 212 µm fraction reaches 36.71% TiO_2 in the concentrate, whereas the finer 063 µm fraction shows significant losses, with 14.44% remaining in the tailings. These results highlight the difficulty of recovering titanium from finer particles, while coarser particles allow more effective concentration. The study underscores the importance of optimizing particle size and refining separation techniques to enhance recovery rates, improve concentrate purity, and develop tailored beneficiation strategies for efficient processing of Makarfi ilmenite ore.

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