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Exploration and characterization of barite mineral from Azara-Nassarawa ore deposits for suitability in industrial applications

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Abstract: Primary concentrations of Azara barite deposit in Nassarawa state, Nigeria were carried out; employing simplified gravity concentration techniques. Particle size distribution, specific gravity, physicochemical and morphological analyses of the sample were conducted. These analyses were done in order to establish process efficacy and effectiveness of gravity concentration processes for recovery of barium from the ore deposit, as well as its suitability in various industrial applications, such as the oil and gas sectors. Thus, microstructural, chemical composition and certain physicochemical characteristics/properties of the mineral sample of Azara-Nassarawa barite were determined. XRD, XRF, SEM and EDS analyses were utilized in determining morphology as well as quantitative and qualitative chemical analyses of the sample. Barite sample with average particle size of -355+150µm was subjected to concentration, adopting jigging and tabling gravity separation as the concentration methods. Hitherto, based on quantitative and qualitative chemical analyses conducted, the sample was composed of about 36.2% BaO and 40.5% Ba, respectively; and also possessed an average specific gravity (SG) of about 3.85. Further, the qualitative analysis of the mineral products of jiggling and tabling indicated that jigging had a concentrate recovery of 130.98% Ba with SG increase of 11.2% while tabling had 89.81% Ba recovery with 8.6% SG increase. Assay and SG results confirm gravity concentration efficiency and thus, establish the barite from Azara-Nassarawa ore deposits suitable for certain industrial applications. This will serve as a tool and a step further towards mitigating existing problems or challenges in mineral concentration and processing of such deposits for industrial purposes.

Keywords: barite, mineral ore, Azara-Nassarawa, gravity concentration, jigging, tabling, concentrate, recovery, specific gravity

1. Introduction

The mineral, barite is one of the most common mineral of barium; composed majorly of barium, as well as sulphur and oxygen (barium sulphate, $BaSO_4$). It is a dense non-metallic mineral with an average SG of 4.5 and a hardness of 3.0 (Mohs' scale). Barite is one of the major sources and principal ore of barium and its compounds whose many uses are nearly hidden among the technical complexities of modern industrial processes and products. It got its name from the Greek word 'barus' which means 'heavy'. According to certain reports, the name was in response to its high SG of 4.5 (Edward, 2022), which is exceptional for a non-metallic mineral. It is one of just a few non-metallic minerals with an average SG of ≥ 4.0. Barite is generally easy to identify, possessing certain unique physical and chemical properties and its industrial applications cannot be over emphasized. Table 1 depicts the general characteristics/properties of a typical barite mineral ore. Although barite contains a "heavy" metal (barium), it is not a toxic chemical because of its extreme insolubility. Basically, it is mostly utilized industrially as drilling muds, high density filler for paper production as well as in the production of rubber and plastics. The high SG of barite also makes it suitable for a wide range of industrial, medical and manufacturing applications. It is extremely important in the petroleum industry where, almost

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about 80% of the world's production of about 44 million tons is being consumed by the petroleum industry in the form of heavy fluids (as weighting agent) which is circulated in rotary drilling. The remaining 20% is chiefly utilized in the production of barium chemicals (Edward, 2022; Nzeh and Hassan, 2018).

Table 1. Physicochemical characteristics of a typical barite (Edward, 2022; Nzeh and Hassan, 2018)

Characteristics/properties	Details
Chemical classification	Sulphate mineral
Chemical formula	$BaSO_4$
Colour	Colourless, white, light shades of yellow, blue, red, green, brown & grey
Streak	White
Cleavage	Very good cleavage, prismatic, basal
Crystal structure	Orthorhombic
Fracture	Uneven/irregular
Lustre	Vitreous to pearly
Melting temperature	1580 ^oC
Fusibility	Yellowish-green Ba flame
Hardness (Mohs)	2.5 – 3.5
Density	4.48 g/cm^3
Specific gravity	4.5
Tenacity	Brittle
Solubility	Low
Optical	Biaxial positive
Refractive	n_α = 1.634-1.636; n_β = 1.636-1.638; n_γ = 1.646-1.648

1.1. Barite deposits and occurrence

Barite is of common occurrence and is often available in three major geologic types of ore deposits ranging from vein, cavity filling to residual or bedded deposits. It belongs to the colloidal mineral like silica. Barite often occurs in tabular crystal-granular form or in compact masses resembling marble. China and India are the major producers of barite with the largest reserves (Edward, 2022; Lefond, 1975). Although, apart from China and India, there have been reports of barite's deposit at certain locations in Nigeria, Brazil, Canada, Chile, Pakistan, Greece, Guatemala, Iran, Ireland (where it was mined in Benbulben), Liberia, Mexico, Morocco, Peru, Romania (Baia-Sprie), Turkey, South Africa (Barberton Mountain Land), Thailand, United Kingdom (Cornwall, Cumbria, Derbyshire, Durham, Perthshire, Argyllshire and Surrey) and in the United States from Cheshire, Connecticut, De Kalb, New Mexico, New York and Fort Wallace. It was also reported to be mined in Arkansas, Connecticut, Virginia, North Carolina, Georgia, Tennessee, Kentucky, Nevada and Missouri (Nzeh and Hassan, 2018; Lefond, 1975). In Nigeria, barite is a hydrothermal deposit originating from hot aqueous solution in joint fault, permeable rock formation and fractures within the middle Benue trough of Nigeria, notably in Benue, Taraba, Adamawa, Gombe, Plateau, Nassarawa, Ebonyi and Cross-river states (Agboola, 2009; MMSD, 2010). Barite occurrence in part of Benue and Nassarawa state, Nigeria; was first discovered by R. B. Tale. The initial reconnaissance work covering Azara/Wuse Akiri district across the River Wuse in Azara local government area of Nassarawa state which lead to the discovery of 18 veins of barite out of which Azara-Nassarawa deposits revealed and indicated reserve of about 730,000 million tonnes of barite within average SG of 4.2 (Bida, 2011). Azara, as the study case falls within the cretaceous sedimentary series in the middle Benue basin. It is a district in Awe Local government of Nassarawa state which is about 97.6 km south of Lafia and 150 km from Lafia to Jos, accessible by road. Howbeit, the barite ore deposit is located at a distance from Lafia interior and is found in former Awe local government, Plateau state which is now Azara local government area in Nassarawa state, Nigeria (Adetoroye, 1998; Oden, 2012; Tanko et al., 2015; Nzeh and Hassan, 2018). Fig. 1 and 2 respectively displays map of the study area as well as barite mineral ore deposits.

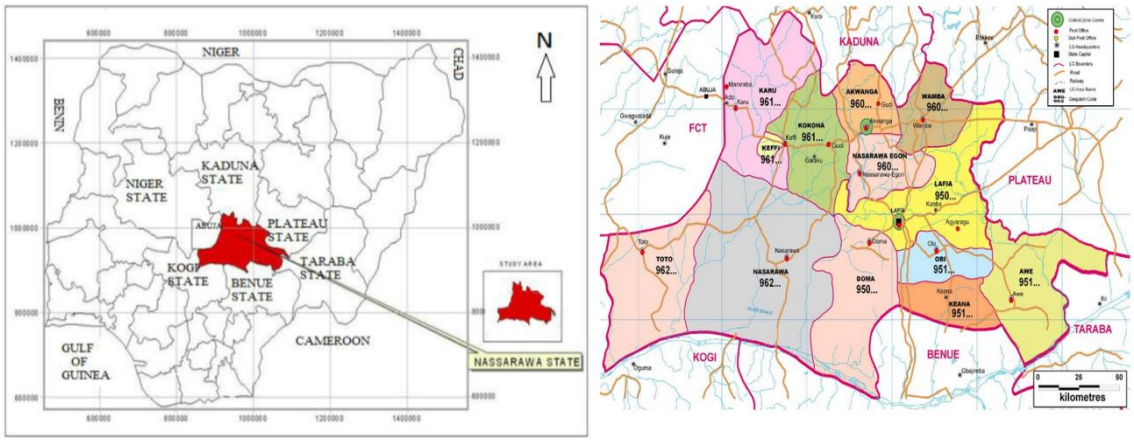
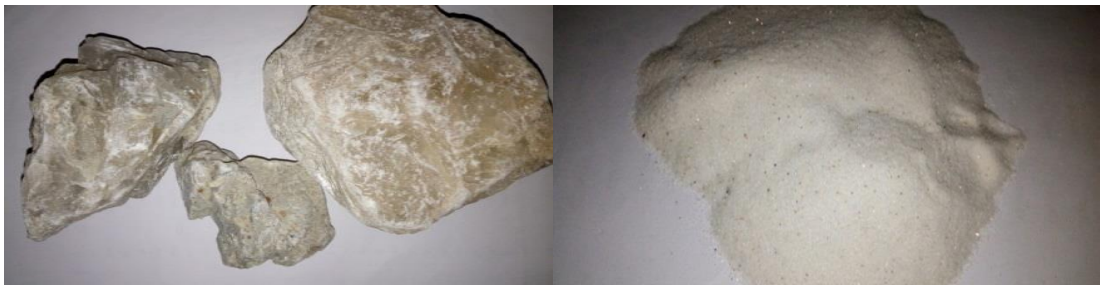


Fig. 1. The geographical map of Nigeria showing the study area



(a) **(b)**

Fig. 2. Azara-Nassarawa barite mineral ore (a) As-received; and (b) Pulverized samples

1.2. Barite applications

Historically, barite is used for the production of barium hydroxide for sugar refining, as white pigments for textiles, papers, plastics, paints and glass production and by the metallurgical industries for brass melting. In crude oil producing countries like Nigeria, barite is basically utilized as weighting agents for drilling fluids/muds by the petroleum oil and gas industrial exploration to suppress high formation pressures and prevent or mitigate the problems caused by blowouts. However, other uses of barite are in added-value applications which include: special fillers in paints and plastics, sound reduction in engine compartments, coat of automobile finishes for smoothness and corrosion resistance, friction products for automobiles and trucks, radiation-shielding cement, glass ceramics and medical applications. It is used by chemical industries to produce barium chemicals (chloride, nitrate, carbonate and hydrate compounds); notably barium carbonate which is used for the manufacture of LED glass for television and computer screens (basically in cathode ray tubes); and for dielectrics. Additional benefit of barite is that it is non-magnetic and thus, does not interfere with magnetic measurements taken in the borehole, either during logging-while-drilling or in separate drill hole logging (Miller, 2009). Howbeit, the most significant barite application is its usage by oil and gas companies when drilling for crude oil or petroleum resources. It is also used for both its physical attributes, such as its potential relatively high SG and chemical inertness (drilling mud additive, construction and functional filler), and for its chemical properties (source of BaO and chemical feedstock). Thus, the principal worldwide application of barite is estimated as 88% for additive to drilling fluids and 6% for chemicals (Nzeh and Hassan, 2018; Hauwa, 2007).

According to reports by Nzeh and Hassan (2018), demand for barite by the manufacturing/oil and gas industries is practically more than the demand for water by humans because of its numerous industrial applications but the supply is still very low as a result of its lack of exploration and exploitation. Despite the somewhat intense mining of barite ore in Azara, Nassarawa state, Nigeria over the years; barite extraction and production has remained low. The need for the most efficient method

of processing the barite mineral, to boost the local supply due to its enormous applications is the reason for the research study since there is steady and increasing demand for barite products due to the numerous industrial applications of the mineral. The quality of the Nigerian barite mineral ore is somewhat moderate, slightly of a low-grade. It is often associated with fluorite, calcite, dolomite, quartz, etc. with major impurities are quartz, iron oxide (goethite), and carbonates of iron, calcium and magnesium. These impurities tend to increase the ore volume, suppress and reduce the SG of the unprocessed barite to about 2.0–3.5. In addition, the cost of mineral processing is increased and if the unprocessed mineral is used in oil and gas applications as drilling muds, without any further upgrade, the oil mills will wear out rapidly. The goethite and silica impurities can be removed by magnetic and gravity separation. If properly beneficiated, the SG of the Nigerian barite can be increased to meet the industrial standard value of range between 4.2 to 4.5 (Ayim and Enoch, 2009). Therefore, this study is primarily focused on the characterization and simplified beneficiation of Azara-Nassarawa barite mineral ore deposits in order to ascertain its suitability and feasibility in oil and gas industrial applications. This will also serve as a tool and a step further towards mitigating existing problems/challenges in the mineral concentration and processing of such deposits for certain industrial purposes.

2. Experimental procedure

Physicochemical characterization was carried out on the barite sample collected from Azara in Awe, Nassarawa state, Nigeria. Gravity separation and SG tests were also conducted. Jigging and tabling gravity concentrations with jigs and shake tables were employed accordingly. Process applications are further explained in this study.

2.1. Sample collection and particle size distribution

The as-received barite ore samples were randomly procured from the above location, cleaned with distilled water to remove dirt and placed to dry. This was reduced and mixed using a sledge hammer. The mixture was further crushed with Schutte Buffalo Hammer Mill for about 30 minutes. Particle size distribution (PSD) analysis of the sample of Azara-Nassarawa barite was then conducted. The pulverized barite ore samples were collected and reduced further using a Shambhavi Impex ball mill in order to pass through the 355µm sieve size. A set of sieves were arranged from the 355µm to 50µm. This sieve arrangement was placed on a pan and the barite ore samples placed on the top sieves (355µm) with a lid cover. The entire arrangement was therefore placed on top of a sieve shaker with Model No: LM200LK3004 LAWKIM. The samples were vibrated for about 25minutes and sieve fractions were collected and weighed. The weighed fractions were used to prepare a spread sheet to examine the PSD and then the 60 % and 80% passing was determined.

2.2. Sample characterisation

To establish the microstructural, physical and chemical properties of Azara-Nassarawa barite ore before and after the mineral separation processes; XRD, XRF, SEM, EDS as well as SG test investigations were carried out accordingly. An XRD analysis was conducted with a GBC Enhance material analyser employing the X-ray diffraction technology to conduct mineral analysis and characterisation. The XRF analysis was carried out with a Skyray Instrument: EDX3600B X-ray fluorescence spectrometer employing a 45kv X-ray tube as voltage. The SEM/EDS analysis of the barite sample after surface preparation was carried out with a Phenom Prox scanning electron microscope (SEM) coupled with an energy dispersive spectrometer (EDS).

2.3. Gravity concentration

2.3.1. Wet tabling process

Shaking table or tabling process is regarded a conventional gravity concentration (CGC) extensively utilized for several years in mineral processing and extractive metallurgy. This method simply involves the separation of mineral particles, typically effective depending on the particle size and shape of the

mineral feed particles, as well as their SG. The shaking table gravity concentration which can either be wet or dry tabling process is comprised of either, the Wilfley, Deister or Holman concentrator types; and they are both built to handle the concentration/upgrade of coarse or somewhat fine mineral feeds. The wet shake table makes use of riffles as vertical stratification takes place on the mineral particles; and this is as a result of the shaking action of the table.

2.3.2. Wet jigging process

Jigs on the other hand, especially the CGC jigs have over the years been referred to as one of the oldest gravity concentration methods. CGC jigs have been employed over the decades in numerous mineral processing applications and have produced somewhat positive and significant results. The wet jigging process is usually operated in a somewhat closed size and efficiently utilized in concentrating relatively coarser minerals. In addition, wet jigging simply employs water pulsation through a bed of minerals in order to obtain stratification which is in accordance to PS and SG of feed mineral particles as well as subsequent selective layer removal. The jigs are practically consisted of two feed (parallel) boxes/hutches as well as the discharges into two sets of cells arranged in series. They basically consist of the production of mineral concentrates and tailings otherwise referred to as underflows and overflows, respectively. The slurry feed introduced is therefore subjected to vertical pulsating movement/force and flows over the two boxes/hutches. High SG coarse mineral particle grains pass through screens and ragging into boxes/hutches and are subsequently removed as underflows (concentrates) whilst slurry discharge remainders flow into the tailing launder as overflows.

2.4. Methodology

Concentration of the barite sample was carried out adopting a Reliance Jig machine for the wet jigging process and a Denver Shake Table for wet tabling process. The samples were screened to a particle size of -355+150 μm and two test samples with known weights were measured out. Sample A weighing 500g and sample B weighing 600g. Both samples were subjected to the two gravity separation processes in order to separate barite from the impurities. Sample A was subjected to the jigging process while sample B subjected to tabling. After the separation processes, sample A had underflows (concentrates) and overflows (tailings) whereas sample B yielded concentrates, middlings and tailings. All samples realized were subsequently placed in a Gen Lab oven to dry in a temperature of 120^{o}C and an average time of 2 hours. More so, the SG was obtained for all sample products and compared to the industrial standard. The microstructure and chemical composition analysis were carried out on the concentrate samples through SEM and EDS analyses, respectively, in order to determine the barium composition and the content of possible impurities still present in the concentrates after concentrations.

On this note therefore, an amount of slurry feed sample was prepared for the jigging process. The jig was rinsed of dirt in order to avoid contamination. The spigot hutch compartment was placed properly with the rubber cork and filled with water to cover the raging in the feed compartment. The sample slurry was fed into the jig and the jigging operation commenced. During the process, overflow materials in the feeding compartment was washed out as overflows. At the end of the process, the spigot of the compartment was opened to realize the product collected as underflows. The underflow and overflow products were dried in an oven and their weights were obtained. This operation was literally aimed at diluting the mineral bed being treated and to control the dilution so that the heavier, smaller particles penetrate the interstices of the bed and the larger, high SG particles fall under a condition probably similar to hindered settling. On the other hand, sample slurry was fed onto the shake table forming a fluidized bed and the tabling operation commenced. During this process, the lighter particles were separated from the denser particles as a result of the shaking/vibrations of the table. The lighter particles fell into a launder as tailings while denser particles went into middlings and concentrates launders. The concentrates, middlings and tailings were allowed to dry in an oven, and their weights recorded. Results of these concentration processes were examined for percentage recovery using the mathematical expression in Equation 1. This was conducted in order to establish the more efficient gravity method on an Azara-Nassarawa barite ore.

$$R_c = \frac{C}{F} \times 100 = \frac{C}{C+T+L} \times 100 \quad (1a)$$

$$R_a = \frac{Cc}{Ff} \times 100 \quad (1b)$$

where R_c = % Recovery of mineral concentrates; R_a = % Recovery by assay; F = Wt. of feed; C = Wt. of concentrates; T = Wt. of tailings; L = Wt. of mineral loss; c = Assay of concentrates; f = Assay of feed

2.5. Specific gravity

Chemical composition analyses as well as SG tests were conducted on the mineral products obtained from both jigging and tabling operations. A densimeter as well as the use of the mathematical expression in Eq. 2 was adequately employed in order to obtain the SG of both concentration products.

$$S.G = \frac{W1}{W2-W3} \quad (2)$$

where S.G = specific gravity; W1 = weight of mineral sample in Air; W2 = weight of water; W3 = weight of water displaced by the sample

3. Results and discussion

Result of the PSD conducted on the as-received barite sample is depicted in Table 2. The result shows that 6.8% by weight of the feed was retained on 355 µm, 12.7% was retained on 250 µm, 17.1% was retained on 180 µm, 29.6% on 125 µm, 17.3% on 90µm, 11.6% on 50 µm, while 4.8% was retained on the pan (-50 µm). From the data in Table 2 and the graphical representation in Fig. 3, it can be observed that the particle size of 355, 250 and 180 µm had about 93.1, 80.4 and 63.3% of undersized particles passing through the sieves, respectively. More so, 125 and 90 µm had 33.7 and 16.4% passing through, respectively, and about 4.8 % passed through the 50 µm sieve and was retained on the base pan. In addition, the particle size with 60% and 80% passing was determined, adopting 'Gaudin Schumann' mathematical relationship in Equations 3 to 5 (Bwala et al., 2021).

Table 2. PSD analysis of the Azara-Nassarawa barite ore sample

Particle size (µm)	Weight		Normal aperture (µm)	Cumm. oversize (%)	Cumm. undersize (%)
	Wt. in g	Wt. %			
+355	50	6.8	355	6.8	93.1
-355+250	93	12.7	250	19.5	80.4
-250+180	125	17.1	180	36.6	63.3
-180+125	216	29.6	125	66.2	33.7
-125+90	126	17.3	90	83.5	16.4
-90+50	85	11.6	50	95.1	4.8
-50	35	4.8	-	-	-
Total	**730**	**99.9**			

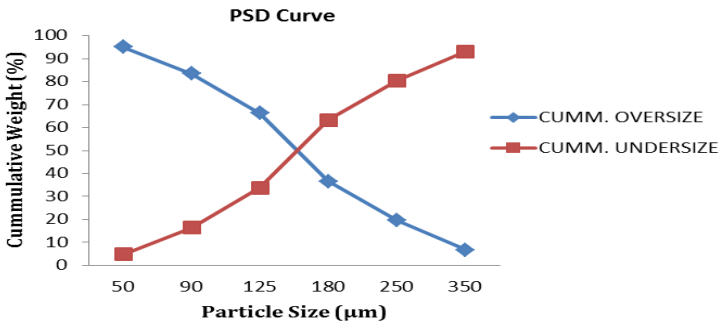


Fig. 3. PSD Curve of the Azara-Nassarawa barite ore sample

$$P(X) = 100\left[{}^{X}/_{K}\right]^{\alpha} \quad (3)$$

where

$$\alpha = \frac{[\log P(X_2) - P(X_1)]}{\log (X_2) - (X_1)} \quad (4)$$

$$\text{Size}_2 = \frac{(\%\ passing\ size_2)^2}{(\%\ passing\ size_1)^2} \times \text{size}_1 \quad (5)$$

Applying 'Gaudin Schumann' mathematical expression in Equations 3 to 5 and the PSD values from Table 2 in order to obtain the particle size of the barite sample at 60% passing (B_{60}) and 80% passing (B_{80}); thus B_{60} and B_{80} were obtained in Equations 6 to 7, as 161.72 and 247.52 µm at 60% and 80% passing, respectively.

$$B_{60} = \left(\frac{60\%}{63.30\%}\right)^2 \times 180\ \mu m = \left(\frac{0.6}{0.6330}\right)^2 \times 180\ \mu m \quad (6)$$

$$B_{80} = \left(\frac{80\%}{80.40\%}\right)^2 \times 250\ \mu m = \left(\frac{0.8}{0.8040}\right)^2 \times 250\ \mu m \quad (7)$$

Hitherto, a SG value of 3.85 was obtained, and confirms the barite ore in Azara-Nassarawa deposit, Nigeria to have a SG value between 3.0 to 4.0 and possesses somewhat low percentage composition of barium and sulphur elements in the presence of other elements (impurities). SG (after gravity separation) was also obtained for all samples; which were related to the industrial standard. The XRF analysis conducted on the as-received barite ore quantitatively showed that the ore is primarily composed of oxides of barium with 36.2%, sulphur with 34.4%, 14.7% titanium, 5.5% vanadium, 1.8% aluminium, and 1.5% silicon, amidst others. More so, the XRD pattern in Fig. 4 confirms the presence of $BaSO_4$ as the longest peaks; therefore establishing that the Azara-Nassarawa ore deposit has a reasonable amount of barite composition as its main mineral constituent. This confirms barite ($BaSO_4$) phase pattern, similar to that of a typical Nigerian barite mineral from Bukkuyum Local Government Area, Zamfara state (Abubakar et al., 2015).

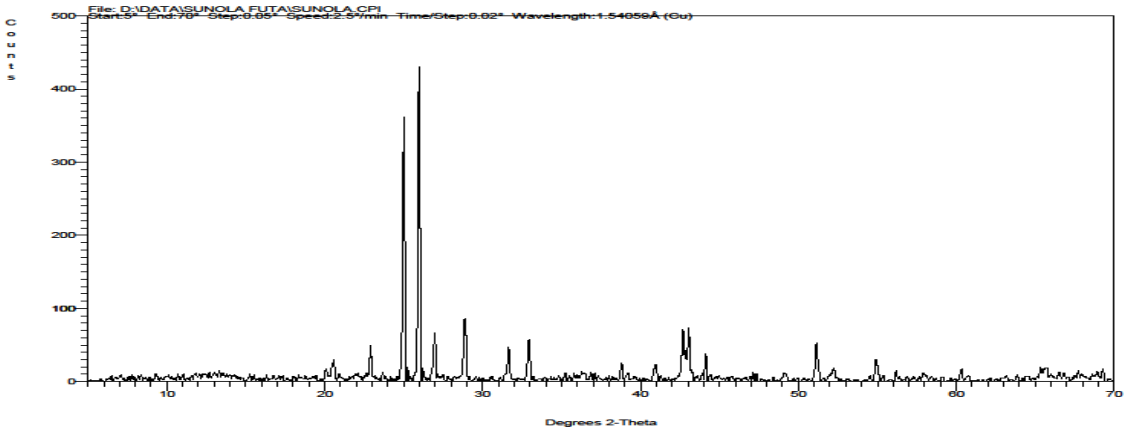
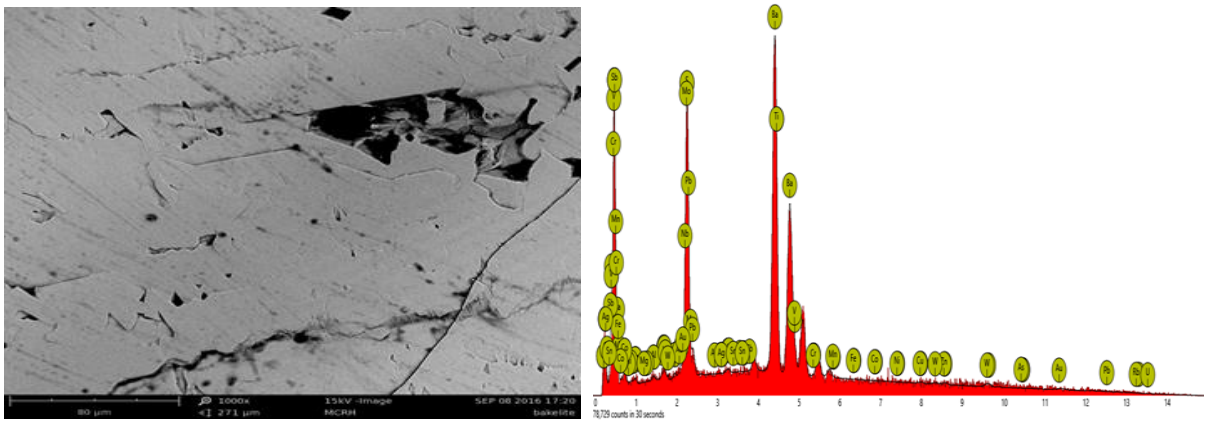


Fig. 4. XRD phase pattern of Azara-Nassarawa barite ore

In addition, the microstructural and chemical composition analysis was carried out on the mineral sample as well as on the concentrates using SEM and EDS, respectively. This was to qualitatively analyse the barite mineral composition which includes the values and the impurities still present in the concentrates after the gravity concentration processes. Similar to the reports by Mgbemere *et al*. (2019); the scan electron photomicrograph revealed the morphology and fracture surface of barite crude that is representative of a typical barite ore deposit in Azara LGA of Nassarawa State, Nigeria (as in Fig. 5a). Also, Fig. 5b represents the Energy Dispersive Spectroscopy (EDS) peak intensities of elemental composition of the as-received sample, revealing various mineral peaks and their different intensities. Barium metal had reasonable distributions and was seen at the highest intensity peak. Thus, the qualitative analysis gave the following compositions: 40.5% barium, 12.6% sulphur, 22.7% oxygen, 5.0% gold, 2.4% molybdenum, 2.3% lead, 1.6% tungsten, 0.7% sodium, 0.6% zinc, 0.4% niobium, 0.3% copper and silicon respectively, 0.2% aluminium, potassium and rubidium respectively, amidst others. This

confirms the XRF results of the as-received sample. More so, this corresponds with the report by Mgbemere, *et al*. (2018). It is also noteworthy that the gold (Au) traces detected in the EDS and not the XRF analysis was as a result of the sample preparation procedure carried out for the SEM analysis.



(a) **(b)**

Fig. 5. (a) SEM Microstructural and (b) EDS Analysis of Azara-Nassarawa Barite ore

Being an old gravity separation technique in mineral processing/extractive metallurgy, its principles are yet to be fully understood regardless. However, certain advantages have made the jigging technique still a preferred gravity concentration method, such as the feasibility of physical/visual inspections and making several adjustments on the process parameters during operation, ability of recovering coarser mineral particles, less comminution requirement and reduction in the generation of excess slime. In view of this, a particle size range of -355+150 µm of feed mineral was utilized for the jigging operation. Jig separation principle of mineral particles with varying SG was effected in a bed resting on a ragging screen. A fluidized bed was obtained as a result of vertical pulsating movement created by incoming flow of water and a diaphragm. The dilating and pulsating movement action on the fluidized bed cause smaller and lighter mineral particles (with low SG and finer size) to form an overflow of tailings whilst denser mineral particles (with high SG and coarser size) tend to sink into and through the ragging forming the underflow of mineral concentrates. The effective agent was the jig bed on top of the screen. Water pulsation or the screen movement kept the bed open in suspension during part of the cycle, so that the particles entering the jig may settle on the bed. Light mineral particles did not penetrate or pass through the jig bed and thus were forced to remain or stay at the upper section of the jig and would discharge onto the top. Further, the jig was provided with the means to bring the mineral particles into a partial suspension at recurrent intervals with certain regularity. This was obtained by sudden drop of screen pulse bed of the fluid thereby causing fluidization for a somewhat short time period. This was as a result of the very packed bed with interstitial water providing a very thick high density suspension which precedes the conditions of the hindered settling. Recovery results of this jigging operation indicated that 76% of the feed was recovered as underflows (concentrates) with an overall assay recovery of about 130.98% barium. However, 15.6% of the mineral particles were recovered as overflows (tailings), and also an 8.4% loss of mineral during the jigging operation. Hence, recovery result of the wet tabling process is represented in Table 3.

On the other hand, feed mineral with similar particle size range was employed in the wet tabling method. The operation process involved the application of flowing water film over an inclined flat surface. The deck in the shaking table was slightly inclined in order to allow mineral feed of about 25 to 40% solids to be introduced into the feed box. Feed particles were distributed by wash water situated along the feed side balance from the launder. There was a longitudinal vibration on the shake table utilizing a slow forward stroke mechanism as well as a rapid return that caused the crawl of the mineral particles along the deck parallel to the motion direction. Mineral particles were therefore subjected to two different forces: the force due to the motion of the table and the forces due to the flowing water film, acting at right angles to that of the table motion. Thus, particles moved in a diagonal motion from

feed end across the deck. Due to the effect of flowing water film which is dependent on the density and size of the feed mineral, the particles fanned out on the shake table, and then the smaller and more dense particles of the feed minerals tide more towards the far end at the concentrate launder while larger and less dense mineral particles ran along the table length and subsequently washed into the tailings launder. The concentrate was separated by an adjustable splitter, giving rise to two different/separate mineral fractions of concentrate products: fraction for mineral middlings and that for high-grade mineral concentrate. Howbeit, the tabling process operated in such a manner that the coarse and light mineral particles moved to the top while the heavy mineral (HM) particles moved to the bottom. Thus, the light mineral gangue particles subsequently ride over the riffles and then discharge at the shake table's lower end alongside the wash water flowing film. The mineral concentrate recoveries were realized at the un-riffled upper section of the table deck.

In furtherance therefore, this wet tabling process has a separation principle that deals with motion or movement of the mineral particles (according to size and SG of the particles) in slurry across the inclined table, oscillating forwards and backwards to the slope (at right angles). This is however done in conjunction with the riffles that holds back particles closest to the deck. This configuration and movement caused the low SG or less dense coarse mineral particles to remain or move closest to the slurry surface, riding over the riffles and discharging the mineral particles over the table's lowest edge. High SG or more dense finer particles moved closer to the deck and were carried along riffles in order to discharge at the table's uppermost. Water nearest to the surface was however retarded by friction caused by absorbed water on the surface. When particles of the feed minerals were fed into the water film, smaller mineral particles moved slowly compared to the motion of larger mineral particles, as they were submerged into a portion of the water film with slower movement. Also, more dense mineral particles or those with higher SG had slower motions compared to less dense or low SG mineral particles, and hence, the production of lateral displacement of the feed mineral particles. Thus, flowing water film efficiently separated smaller, dense or HM particles from coarser, less dense or light mineral particles. The recovery results of this tabling operation as represented in Table 4 showed 52.3% of the feed was recovered as concentrates, 40.3% as middlings, and 7% as tailings with 0.3% loss. Overall, the wet tabling process had about 89.81% Ba recovery. Howbeit, it is imperative to note that both the jigging and tabling concentration processes had specific mineral losses during operation, of about 8.4% and 0.3%, respectively. This was thus considered during the recovery calculations, in order to determine the overall performance of both concentration methods.

Table 3. Results of gravity concentration of Azara-Nassarawa barite by jigging method

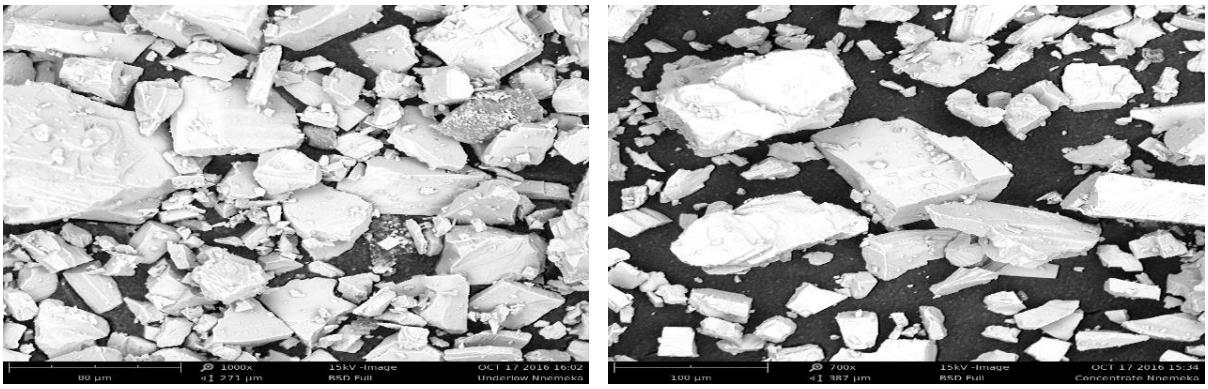
Particle size	**Feed**	**Underflow of concentrate**		**Overflow of tailing**		**Loss of mineral**		**Recovery by assay**
-355 + 150µm	500g	380g	76%	78g	15.60%	42g	8.40%	130.98%

Table 4**.** Results of gravity concentration of Azara-Nassarawa barite by tabling method

Particle size	**Feed**	**Concentrate**		**Middling**		**Tailing**		**Loss of mineral**		**Recovery by assay**
-355 + 150µm	600g	314g	52.30%	242g	40.30%	42g	7%	2g	0.30%	89.81%

Fig. 6 represents scan electron photomicrographs of the concentrates after jigging and tabling processes, respectively. It displayed clearer SEM microstructures than that of the as-received sample and also somewhat similar to the microstructure of a typical barite mineral. In terms of the distribution of particle sizes and shapes, there were no significant microstructural changes observed for both samples. However, large and small particle grains were observed for both samples with varying pore structures. Fig. 6b displayed a larger pore structure than Fig. 6a. These are indications that both samples are suitable for pyro-hydrometallurgical treatments, displaying very good extraction possibilities and high dissolution rate feasibility when subjected to subsequent downstream hydrometallurgical measures for efficient and selective extraction of barium as well as other value or critical metals. Table

5 shows composition comparisons for both jigging underflows and tabling concentrates. The result confirmed higher percentage contents of barium with 69.8% and 69.5% for jigging and tabling concentrates, respectively. This can be compared to the initial quantitative and qualitative analysis of the as-received barite sample of 36.2% and 40.5% barium, respectively. This is an indication that both gravity concentration methods can successfully be adopted for barite mineral upgrade, and thus in the recovery of barium as well as in the reduction of certain mineral impurities found in the barite ore. This is also in agreement with previous investigations reported elsewhere (Nzeh and Hassan, 2018; Mgbemere et al., 2018, 2019).



(a) **(b)**

Fig. 6. SEM microstructural of the concentrates after (**a**) Jigging and (**b**) Tabling operations

Table 5. Chemical composition of the as-received mineral, jigging and tabling concentrates

Composition, %	**Ba**	**S**	**Ti**	**Nb**	**V**	**W**	**P**	**Si**	**Fe**	**Al**	**Cu**	**Sn**	**Rb**	**Mo**	**Na**	**Zn**	**Pb**	**K**
Atomic No., Z	56	16	22	41	23	74	15	14	26	13	29	50	37	42	11	30	82	19
Feed XRF	36.2	34.4	14.7	-	5.5	0.1	0.4	1.5	0.2	1.8	-	0.3	-	0.1	-	0.1	-	0.1
Feed EDS	40.5	12.6	-	0.4	-	1.6	-	0.3	-	0.2	0.3	-	0.2	2.4	0.7	0.6	2.3	0.2
Jigging EDS	69.8	7.4	-	0.2	-	0.3	-	0.2	-	0.1	0.2	-	0.1	0.2	0.4	0.3	1.1	0.1
Tabling EDS	69.5	8.0	-	0.2	-	0.0	-	0.3	-	0.1	0.2	-	0.0	0.0	0.6	0.3	0.0	0.2

Finally, the SG results of the as-received barite ore and the concentrates from both jigging and tabling gravity separation methods are displayed in Table 6. It was observed that the jigging and tabling wet gravity concentrates had increased SG of 4.28 and 4.18 with a percentage increase of about 11.2% and 8.6%, respectively. This is therefore an indication that both jigging and tabling gravity concentrations are obviously efficient and suitable for the mineral concentration and subsequent SG upgrade of the barite mineral ore for oil and gas purposes as well as its utilization in other industrial applications by the manufacturing and production industries. A graphical representation and comparison of the SG results obtained is displayed in Fig. 7.

Table 6. SG of the Azara-Nassarawa barite samples

SAMPLES	SG
STANDARD	*4.20 – 4.50*
AV. STANDARD	*4.35*
A	3.85
B	4.28
C	2.30
D	4.18
E	3.88

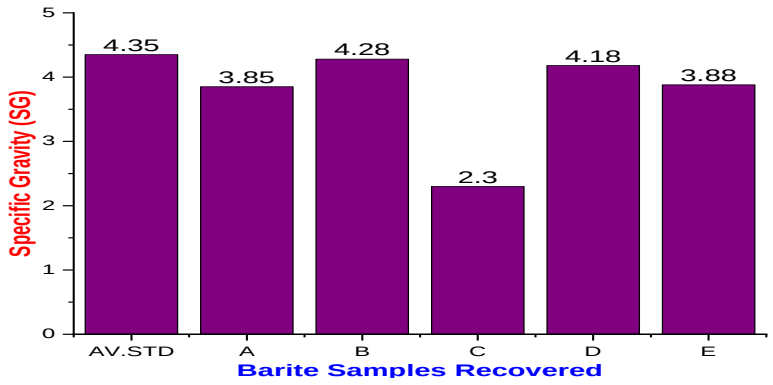


Fig. 7. Graphical representation of the SGs of the barite samples in comparison with the industry standard (Sample A = As-received barite ore sample; Sample B = Underflows after jigging; Sample C = Overflows after jigging; Sample D = Concentrates after tabling; Sample E = Middling after tabling)

4. Conclusions

The deductions from this study explain that the barite mineral ore from Azara-Nassarawa deposits basically contains about 36.2% to 40.5% barium as major constituent. Results from the study also showed efficiency of jigging and tabling gravity concentration methods on the percentage recovery and SG of the barite sample. Jigging method proved to be more effective than tabling method, utilizing mineral particle size range between 150 to 355 µm for both operations. A concentrate recovery of about 52.30% and 89.81% barium recovery was realized after the tabling process. However jigging process produced higher recoveries of 76% concentrates and about 130.98% barium recovery. Howbeit, it is noteworthy and can be deduced from the study that concentration of HMs with SG difference can be accomplished in fluidized beds by a pulsating fluid current in order to produce stratification. Smaller and denser mineral particles may penetrate the bed interstices and therefore larger, high SG mineral particles fall under similar conditions or principles of hindered settling. This can be attributed to the sufficient treatment and control of dilution of the mineral bed. In view of this, it is imperative that acceptable recovery conditions should be maintained or controlled in order to achieve optimal (fluidized) bed conditions. Essentially, it is quite noteworthy that higher separation efficiencies can be obtained by the jigs, especially in the case where there is relatively large SG difference between or within the mineral particles. Thus, it is safe to conclude that a good mineral concentration with optimal recovery within a wide range of particle sizes is very feasible and highly dependent on the mineral particles' SG difference. However, jigging gravity separation possesses relatively large unit capacity on the classified mineral feed and may also obtain high recoveries of value minerals with particle size up to 150 µm. The wet tabling process on the other hand denotes a process mechanism regarded as the most metallurgical effective form of gravity concentration. This encompasses the concentration of smaller and more difficult flow streams as well as the production of finished concentrates from products of other types of gravity concentration systems. Finally, it can be deduced from the study that the Azara-Nassarawa barite sample was upgraded to a range of 4.18 to 4.28 SG from its original 3.85 SG. It was determined that the Jigging concentrates had a SG of 4.28 and a percentage increase of about 11.2% at a particle size of -355+150µm. This was a better result than the tabling process with 4.18 SG and a percentage increase of about 8.6%. This meets the industrial standard of 4.20 to 4.50 SG required by the oil and gas and other production/manufacturing industries. In conclusion therefore, the results of this investigation have thus confirm the earlier investigations by Nwoko and Onyemaobi (1997) and established the suitability of Azara-Nassarawa barite for oil and gas and other industrial applications.

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