

Comminution Behavior and Liberation Characteristics of Zankan Spodumene for Lithium Recovery

Usman Muhammad Akindele^{a,c,*}, Segun Talabi^{b,e}, Yahaya Taiwo^b, Jeleel Adekunle Adebisib^b,
Rasheedat Modupe Mahamood^{b,d}, Suleiman Abdulkareem^a, Ismaila Idowu Ahmed^b

^aDepartment of Mechanical Engineering, University of Ilorin, Ilorin, Nigeria,

^bDepartment of Materials and Metallurgical Engineering, University of Ilorin, Ilorin, Nigeria,

^cDepartment of Metallurgical Engineering, Kaduna Polytechnic, Kaduna, Nigeria,

^dDepartment of Mechanical and Construction Engineering, Northumbria University, Newcastle Upon Tyne, UK,

^eDepartment of Energy, Oak Ridge National Laboratory, 5200,1 Bethel Valley Rd, Ridge, TN 37830, United States.

Keywords:

Spodumene
Comminution
Lithium-ion batteries
Particle liberation
Energy material

* Corresponding author:

Usman Muhammad Akindele
usmanakindele@kadunapolytechnic.edu.ng

Received: 2 January 2026

Revised: 14 February 2026

Accepted: 18 March 2026



ABSTRACT

The energy requirement for liberating valuable minerals from their associated gangue is determined by the comminution process of the ores, which is often quite expensive and can be as high as 50% of the total energy needed in mineral processing plants. Hence, the need for determination of Zankan Spodumene comminution parameters with no prior data sheet cannot be overemphasised. Spodumene obtained from Zankan Village, Nigeria, was subjected to grindability test using granite and magnetite as reference materials. Sieve analysis was carried out using laboratory sieve shaker. Homogenized samples were obtained by Coning-quartering and riffle splitter methods were processed for chemical compositional analysis using ICP-OES. Lastly, work index of Zankan spodumene was determined, in line with Bond modified energy equation. Grindability tests showed that $F_{80\%}$ for Spodumene, Granite and Magnetite were 553.82, 357.68 and 418.85 μm , while $P_{80\%}$ were 257.02, 177.42 and 242.67 μm , respectively, work index was then obtained to be 16.3 kWh/t and 10.24 kWh/t considering Granite and Magnetite as reference materials. Liberation study shows 75 μm sieve size as the liberation size, having the highest-grade value of lithium content. Experimental parameters attained from this study will be relevant to the processing of the Zankan Spodumene as a critical primary source of lithium for next-generation energy storage systems, particularly for lithium-ion battery production.

© 2026 Journal of Materials and Engineering

1. INTRODUCTION

The growing projection of lithium resources has necessitated the development of an efficient process route being an cleaner alternatives and energy storage capabilities making renewable technologies to cut back from traditional infrastructure networks, so, the demand for lithium has been forecasted to expand significantly over the coming decade as a critical element in the chemistry of lithium-ion batteries, then, to recover lithium products from its host rocks [1], particularly the comminution process and its parameters. These parameters over the year still remain the most considered tools in the design, assessment and optimisation of comminution units around the globe [2]. Comminution of solid materials involves a sequence of crushing and grinding to reduce the particle size of run-of-mine to the desired level [3, 4]. It is an important test in the design of beneficiation plants [5]. Comminution parameters provide information about the particle size distribution required for mineral liberation and the determination of work index [6-8].

However, these parameters (work index and liberation size determination) are an energy-intensive process, which amounts to 30-50% of the total power consumption in mineral processing plants [9, 10] while 30-70% of the overall energy used goes to mining operations [11]. Reducing the energy consumed, in turn cutting down the associated cost of grinding working index in the absence of standardised machinery, though determination of work index

of materials is done in different ways, which has been explored by various researchers as summarised in Table 1, ranges from preparation of the ore, types, quantity, as well as the feed size of the ore and many other conditions [12].

The Bond Work Index (BWI) is widely used to quantify ore grindability and to estimate the specific energy demand for size reduction. In lithium processing operations, high BWI values are directly linked to increased electrical energy consumption and operating costs, which are increasingly scrutinised in the context of sustainable battery-materials production [13]. The comparative grindability test was considered by [9, 14-16] for the determination of the work index of an ore. Also, determination of Liberation size which has to do with department of mineral of interest across the particle size determine by chemical compositional examination [3, 17], for which Insufficient liberation may lead to poor flotation selectivity, elevated impurity levels, and reduced lithium recovery, thereby compromising downstream processing efficiency and final product quality [18, 19]. Within this context, the present study investigates the comminution behavior, Bond Work Index, and liberation characteristics of Zankan spodumene ore, with the objective of assessing their implications for lithium recovery and suitability for energy-storage applications. By linking mineral processing performance with the quality demands of lithium-ion battery materials, this work will contribute to the development of more energy-efficient and resilient lithium supply chains.

Table 1. Different methods for work index determination [12].

Methods	Sample Mass Required (Kg)	Relative error (%)	Remarks
Bond (Standard)	10	-	-
Todorovic	2	0.3	-
Gharehgheshlagh	10	3.5	Size calculation
Host	5	8.4	Applicable to all mills, reference ore required
Ahmadi	5	6.8	-
Ahmadi (Mod.)	5	3.5	Database required
Berry	1	6.3	Applicable to all mills, reference ore required
JKBBM	4	3.5	-
Kapur	3	9.5	-
Kapur (Mod.)	3	3.5	Database required
Carr	3	5.1	-

Carr (Mod.)	5	1.7	Applicable when using three cycles
Smith & Lee	2	16.6	Methods not in use
Lewis	2	-	Low cum. passing for homogenous ores
MiniBond	4	-	Used for calculating product of any size
Armstrong	3	-	Test for wet grinding in a rod mill
Aksani	2	-	Low cum. passing for homogenous ores
Anconda	2	-	Applicable to all mills, reference ore required

2. EXPERIMENTAL PROCEDURE

2.1 Material preparation and experimental tests

The sample materials used for experimental work were obtained from Zankan village, Jemaa LGA of Kaduna state, Nigeria. Ore Samples collected at five different pits were crushed using a jaw crusher operated at 415V, 50Hz, 4000w, and 8.1A. The crushed ore samples were then pulverised using a Ball Mill that was operated at 220-240V, 50Hz, 370W, and 3.8A. The ground ore was then homogenised and sampled using coning- quartering and riffle splitter methods to achieve a representative sample for chemical and work index determination. Granite and Magnetite obtained from Kaduna and Kogi States, respectively, were used as reference materials for the determination of the work index of the spodumene. The crusher was powered and the materials were fed slowly into the crusher’s gape. Then, crushed materials were taken to a ball milling machine with 12 steel balls of 3.5 cm in diameter, and each ball weighed 222 grams, placed together with the crushed ore.

2.2 Methods

2.2.1 Determination of liberation size

Sieve size analysis was conducted on the unbiased representative sample and the distribution weighed and recorded. The highest sieve size was 250 µm and the lowest aperture was 38 µm. The chemical characterisations of the different sieve apertures were performed using inductively Coupled Plasma- optical Emission Spectroscopy (ICP-OES; Shimadzu model 7000) based on ASTM E1479-14 standard for corresponding department of the element of interest across the sieves.

2.2.2 Determination of Work Index

The process was conducted on a Rotap sieve shaker; the sample was placed on a nest of sieves with the coarsest on top and the finest at the bottom (ASTM C136), and the set of sieves was vibrated for thirty minutes on the sieve shaker. Root 2 series ($\sqrt{2}$) used for the arrangement of the sieves. Weights were tabulated and recorded against their sieve and 80% passing (F_{80} , P_{80}) was determined according to the Gate Gaudin-Schuhman equation, see Equation 1.

The work index of the Zankan spodumene was determined using the Berry–Bruce method, which entails milling two mineral samples of the same weight. Both the test and reference materials were crushed and pulverised for one hour. A reference material of known work index, Granite, with a theoretical work index of 15.13 kWh/ton and magnetite of 15.86 kWh/ton [16, 20, 21] were used. The work index of the test material (Zankan spodumene) was thereafter computed using Bond’s energy equation, see Equation 2 [22].

$$80\% \text{ Cummulative passing size} = \left(\frac{80\%}{\% \text{ passing size 1}} \right)^2 \times \text{size 1} \tag{1}$$

$$W_{it} = W_{ir} \times \frac{\left(\frac{1}{\sqrt{P_r}} - \frac{1}{\sqrt{F_r}} \right)}{\left(\frac{1}{\sqrt{P_t}} - \frac{1}{\sqrt{F_t}} \right)} \tag{2}$$

Where;

W_{ir} = work index of the reference ore;

W_{it} = work index of the test ore;

P_r = 80% passing of the product (reference material);

P_t = 80% passing of the product (test material);

F_r = 80% passing of the feed (reference material);

F_t = 80% passing of the feed (test material).

3. RESULTS AND DISCUSSION

3.1 Liberation size determination

The lithium contents of various sieve sizes were determined by ICP-OES, and the results are listed in Table 2. The prepared sample was sieved with

particle sizes ranging from 250 to 38 μm . It shows the results of the assay grade of lithium in the various sieve sizes of the head sample. The coarsest sieve size used was 250 μm and the finest was 38 μm . The results showed that the 75 μm sieve size is the liberation size, having the highest-grade value of 1.32% lithium content.

Table 2. Chemical analysis result of the head sample at various sieve sizes.

Sieve Size (μm)	Elemental Composition [Wt. %]							
	Li	Fe	Ca	Si	Al	K	Mg	Na
250	0.43	1.37	0.55	29.9	9.3	0.52	0.16	1.16
180	0.29	1.22	0.72	31.0	7.9	0.41	0.05	0.76
150	0.49	0.98	0.35	30.9	8.5	0.93	0.37	0.77
106	1.06	1.43	1.31	33.3	10.4	0.82	0.26	1.62
75	1.32	1.66	1.92	32.2	9.4	0.61	0.16	0.71
50	1.16	0.65	0.63	32.2	8.4	0.03	0.43	1.14
38	1.00	1.10	0.33	33.7	8.8	0.42	0.04	0.75

3.2 Work index determination

Particle size analyses conducted on the samples of each pit resulted in the data tabulated in the Table 3 and 4, which show cumulative percent weight passing for both the feed and product obtained through crushing and grinding of the test materials. The work index of each was then determined. In contrast, samples from the five pits were combined and the work index was also determined using magnetite in addition to granite as reference material, cumulative weight percentage passing of

the particle sizes of the test material (Spodumene) and reference materials, Granite and Magnetite (Feed and Product), shown in Table 5. From the results, the particle size fractions of the test material and the reference materials show a normal distribution pattern, indicating that the particle size fractions of the three materials respond to the theories of comminution. That is, the energy consumed in size reduction is proportional to the area of the new surface produced. The 80% passing for the "Feeds" and "Products" were obtained according to Equation 1.

Table 3. Result of sieve size analysis showing the cumulative percent weight passing of the "Feed" of pit I-V.

Particle Size (μm)	Cumulative % Weight Passing [Feed]				
	PIT I	PIT II	PIT III	PIT IV	PIT V
+1000	99.75	99.65	99.75	99.45	100.0
-1000+710	92.65	92.20	94.70	91.35	93.75
-710+500	86.25	84.95	88.10	85.50	83.25
-500+355	80.55	79.05	80.60	75.40	75.95
-355+250	63.90	63.75	71.20	65.00	60.80
-250+180	47.05	46.15	50.60	48.95	37.10
-180+125	32.40	30.65	34.90	35.15	23.10
-125+90	14.90	18.35	19.65	23.15	14.30
-90+63	10.30	13.35	15.65	20.00	09.30
-63+45	05.10	04.35	07.65	08.50	05.80
-45 (Pan)	00.00	00.00	00.00	00.00	00.00

Table 4. Result of sieve size analysis showing the cumulative percent weight passing of the "Product" of pit I-V.

Particle Size (µm)	Cumulative % Weight Passing [Product]				
	PIT I	PIT II	PIT III	PIT IV	PIT V
+1000	100.00	99.90	100.00	99.95	100.00
-1000+710	98.25	97.10	98.45	97.80	98.95
-710+500	94.90	95.55	97.60	97.00	95.80
-500+355	92.80	92.40	92.40	92.20	89.20
-355+250	83.90	82.20	84.35	85.70	84.70
-250+180	73.35	72.75	77.40	76.15	69.70
-180+125	64.10	65.25	61.60	51.85	56.65
-125+90	50.55	51.45	38.10	34.95	31.50
-90+63	27.35	33.25	25.70	19.20	19.75
-63+45	15.50	20.00	19.70	15.20	14.70
-45 (Pan)	00.00	00.00	00.00	00.00	00.00

Then, the mathematical expression by Equation 1 was used to determine 80% passing (F_{t80} & P_{t80}) values so as to calculate the ore work index (W_{it}).

Thus;

Pit I; $F_{t80} = 391.8 \mu\text{m}$, $P_{t80} = 214.1 \mu\text{m}$

Pit II; $F_{t80} = 363.6 \mu\text{m}$, $P_{t80} = 217.7 \mu\text{m}$

Pit III; $F_{t80} = 315.6 \mu\text{m}$, $P_{t80} = 192.2 \mu\text{m}$

Pit IV; $F_{t80} = 399.6 \mu\text{m}$, $P_{t80} = 198.7 \mu\text{m}$

Pit V; $F_{t80} = 393.9 \mu\text{m}$, $P_{t80} = 237.1 \mu\text{m}$

These parameters were used to obtain the corresponding work index of each pit, following the mathematical relations in Equation 2 and W_{it} of the pit 1-5 are: 18.85 kWh/t, 21.91 kWh/t, 21.23 kWh/t, 16.06 kWh/t and 23.1 kWh/t respectively. However, the differences in the distribution obtained could be attributed to the mineralogical setting of each pit, among other factors. Meanwhile, a combination of the samples from all the pits (Blend) was experimented with, this time not just Granite as reference material, but Magnetite as well. Thus, the results presented in Table 5.

Table 5. Result of sieve size analysis of the "feed" and "product" of reference materials and Blend.

Particle Size (µm)	Cumulative % Weight Passing [Feed]					
	Feed (Magn.)	Product (Magn.)	Feed (Gran.)	Product(Gran.)	Feed (BL)	Product (BL)
+1000	97.45	99.30	98.56	99.00	99.20	99.65
-1000+710	95.55	98.70	98.00	98.90	92.95	98.50
-710+500	80.25	91.25	85.50	97.85	85.25	93.60
-500+355	73.65	88.10	79.70	96.90	78.05	88.50
-355+250	61.70	86.85	69.50	94.90	65.70	78.90
-250+180	38.15	68.90	41.35	80.80	48.55	65.25
-180+125	29.45	58.65	30.40	67.15	35.25	45.40
-125+90	11.10	37.40	16.40	45.10	19.25	33.50
-90+63	10.05	24.80	13.45	26.75	14.25	25.50
-63+45	06.80	18.50	07.50	22.20	08.75	18.65
-45 (Pan)	00.00	00.00	00.00	00.00	00.00	00.00

Thus;

From Equation 1

$F_t = 553.82 \mu\text{m}$; $P_t = 257.02 \mu\text{m}$; $F_{rG} = 357.68 \mu\text{m}$;
 $P_{rG} = 177.42 \mu\text{m}$; $F_{rM} = 418.85 \mu\text{m}$; $P_{rM} = 242.67 \mu\text{m}$

Using Equation 2

$$W_{it} = W_{ir} \left(\frac{1}{(177.42)^{\frac{1}{2}}} - \frac{1}{(357.68)^{\frac{1}{2}}} \right) / \left(\frac{1}{(257.02)^{\frac{1}{2}}} - \frac{1}{(553.82)^{\frac{1}{2}}} \right)$$

$$W_{it} = 1.077 \times 15.13$$

$$W_{it} = 16.3 \text{ kWh/t (with Granite as reference material)}$$

Also;

$$W_{it} = W_{ir} \left(\frac{1}{(242.67)^{\frac{1}{2}}} - \frac{1}{(418.85)^{\frac{1}{2}}} \right) / \left(\frac{1}{(257.02)^{\frac{1}{2}}} - \frac{1}{(553.82)^{\frac{1}{2}}} \right)$$

$$W_{it} = 0.646 \times 15.86$$

$$W_{it} = 10.24 \text{ kWh/t (with magnetite as reference material)}$$

Therefore, the amount of energy required to comminute Spodumene is 16.3 kWh/t and 10.24 kWh/t.

4. CONCLUSION

The Liberation study shows 75 µm sieve size as the liberation size, having the highest-grade value of lithium content and this value is a good percentage as Feed to the Concentrator or extraction unit for significant upgrade and high lithium products. While the amount of energy required to comminute one ton of Zankan Spodumene is on average, 13.27 kWh/t. Therefore, results of this study show that the comminution behavior and Bond Work Index of Zankan spodumene ore provide essential insight into the crushing and grinding energy requirements, which represent a major component of the overall energy demand in hard-rock lithium processing as well liberation characteristics identified in this work indicate that achieving an optimal balance between particle size reduction and energy consumption is critical for maximizing flotation efficiency and concentrate quality in the next face of the research. More so, adequate liberation improves spodumene–gangue separation, minimises impurity entrainment, and supports the production of high-grade concentrates suitable for downstream thermal and hydrometallurgical conversion into battery-grade lithium compounds.

Acknowledgement

The research work was funded by Tertiary Education Trust Fund (TETFUND) under the auspices of the National Research Fund (NRF) with Grant Reference: TETF/DR&D-CE/NRF/2020/SETI/31/ Vol.1. The financial support is duly acknowledged.

REFERENCE

[1] J. Tian *et al.*, “A novel approach for flotation recovery of spodumene, mica and feldspar from a lithium pegmatite ore,” *Journal of Cleaner Production*, vol. 174, pp. 625–633, Feb. 2018, doi: 10.1016/j.jclepro.2017.10.331.

[2] N. S. Nzeh, A. P. I. Popoola, D. Okanigbe, S. O. Adeosun, and A. A. Adeleke, “Work index evaluation of Rayfield-Jos columbite mineral for effective processing and recovery of niobium and tantalum,” *Materials Today: Proceedings*, vol. 105, pp. 131–138, 2024, doi: 10.1016/j.matpr.2023.08.059.

[3] E. Obassi, D. T. Gundu, and U. M. Akindele, “Liberation Size and Beneficiation of Enyigba Lead Ore, Ebonyi State, South-East Nigeria,” *JMMCE*, vol. 03, no. 03, pp. 125–133, 2015, doi: 10.4236/jmmce.2015.33015.

[4] B. A. Wills, *Wills’ Mineral Processing Technology: An Introduction to the Practical Aspects of Ore Treatment and Mineral Recovery*, 7th ed. Oxford: Elsevier Science & Technology, 2011.

[5] A. Mwanga, J. Rosenkranz, and P. Lamberg, “Testing of Ore Comminution Behavior in the Geometallurgical Context—A Review,” *Minerals*, vol. 5, no. 2, pp. 276–297, May 2015, doi: 10.3390/min5020276.

[6] D. Sandmann and J. Gutzmer, “Use of Mineral Liberation Analysis (MLA) in the Characterization of Lithium-Bearing Micas,” *JMMCE*, vol. 01, no. 06, pp. 285–292, 2013, doi: 10.4236/jmmce.2013.16043.

[7] C. Wang, S. Nadoski, O. Mejia, J. Drozdiak, and B. Klein, “Energy and cost comparisons of HPGR-based circuits with the SABC circuit installed at the Huckleberry mine,” in *Proc. 45th Can. Mineral Processors Conf.*, Ottawa, ON, Canada, 2013.

[8] D. M. Weedon, T. J. Napier-Munn, and C. L. Evans, “Studies of mineral liberation performance in sulphide comminution circuits,” in *Sulphide Deposits—Their Origin and Processing*, P. M. J. Gray *et al.*, Eds. Dordrecht, Netherlands: Springer, 1990, pp. 135–154, doi: 10.1007/978-94-009-0809-3_9.

[9] E. A. P. Egbe, E. Mudiare, O. K. Abubakre, and M. I. Ogunbajo, “Determination of the Bond work index of Baban Tsauni (Nigeria) lead-gold ore,” *Eur. Sci. J.*, vol. 9, no. 12, pp. 1857– 7431, 2013.

[10] T. J. Napier-Munn, Ed., *Mineral comminution circuits: their operation and optimisation*, Repr. with minor corr. in JKMRRC monograph series in mining and mineral processing, no. 2. Indooroopilly, Queensland: Julius Kruttschnitt Mineral Research Centre, 2005.

[11] S. Nadolski, B. Klein, A. Kumar, and Z. Davaanyam, “An energy benchmarking model for mineral comminution,” *Minerals Engineering*, vol. 65, pp. 178–186, Oct. 2014, doi: 10.1016/j.mineng.2014.05.026.

- [12] V. V. Lvov and L. S. Chitalov, "Comparison of different ways of determining the Bond ball work index," *Int. J. Mech. Eng. Technol.*, vol. 10, no. 3, pp. 1180-1194, 2019.
- [13] B. A. Wills and J. A. Finch, *Wills' mineral processing technology: An introduction to the practical aspects of ore treatment and mineral recovery*, 8th ed. Oxford, U.K.: Butterworth-Heinemann, 2015. doi: 10.1016/C2010-0-65478-2.
- [14] E. Obassi, D. T. Gundu, and U. M. Akindele, "Determination of work index of Arufu lead ore, Nasarawa State, North-Central Nigeria," *Int. J. Eng. Sci.*, vol. 4, no. 2, pp. 10-14, 2015.
- [15] K. J. Olatunji and A. G. Durojaiye, "Determination of Bond index of Birnin- Gwari Iron Ore in Nigeria," *JMMCE*, vol. 09, no. 07, pp. 635-642, 2010, doi: 10.4236/jmmce.2010.97045.
- [16] A. H. Umar, S. A. Yaro, M. Abdulwahab, and M. R. Dodo, "Characterization of Sokoto phosphate rock for beneficiation," *JORMAR*, vol. 10, no. 2, pp. 74-93, 2016.
- [17] S. L. Gay, "A liberation model for comminution based on probability theory," *Minerals Engineering*, vol. 17, no. 4, pp. 525-534, Apr. 2004, doi: 10.1016/j.mineng.2003.11.012.
- [18] S. E. Kesler, P. W. Gruber, P. A. Medina, G. A. Keoleian, M. P. Everson, and T. J. Wallington, "Global lithium resources: Relative importance of pegmatite, brine and other deposits," *Ore Geology Reviews*, vol. 48, pp. 55-69, Oct. 2012, doi: 10.1016/j.oregeorev.2012.05.006.
- [19] G. W. Lederer et al., "USGS critical minerals review," *Mining Engineering*, May 2025.
- [20] N. L. Weiss, *Mineral Processing Handbook*. New York, NY, USA: American Institute of Mining, Metallurgical, and Petroleum Engineers, Inc., 1985.
- [21] S. A. Yaro, "Development of process route for the beneficiation of Mallam Ayuba manganese deposits to ferromanganese feed grade," Ph.D. dissertation, Ahmadu Bello Univ., Zaria, Nigeria, 1997.
- [22] B. A. Wills and J. E. Finch, *Wills' mineral processing technology: an introduction to the practical aspects of ore treatment and mineral recovery*, Eighth edition. Amsterdam Boston, Mass Heidelberg: Elsevier, 2016.