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DETERMINATION OF WORK INDEX OF SPODUMENE FROM KENTICHA ORE, SOUTHERN ETHIOPIA

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Abstract: The samples used for this study were granite and spodumene ore (2000 grams) (divided into four equal parts with 500 g), 500 g for chemical analysis, and granite (500 g) was separately used as reference ores from the Kenticha ore deposit. Each test ore was weighed at 2000 grams, and the reference ore was weighed at 500 grams, and all were ground in a lab ball mill under the same conditions. Size analysis of the feed to the ball mill and the output from the ball mill was performed on test ore and reference ore, with the results properly tabulated. The feed and discharge particle sizes for the samples into the ball mill were calculated using the Gaudian–Schumann formula to ensure an 80% passing rate. The work index for spodumene ore, as cited in the literature, is found in the range of 10.4–11.5 kWh/ton. In this study, the Modified Bond Index method was used to determine the work index of spodumene samples from Kenticha ore using granite as a reference ore. The work index of the Kenticha spodumene ore was discovered to be 11.391 kWh/ton.

***Keywords*:** *Bond's equation, spodumene ore, granite, size analysis, work index*

1. INTRODUCTION

Ethiopia's resources include rare metals like gold, platinum, nickel, copper, iron, and chromium, as well as industrial minerals and rocks like kaolin, feldspar, clay, asbes-

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tos, and talc. The majority of Ethiopia's metallic ore deposits are gold, platinum, tantalum, nickel, and iron (Tadesse et al. 2003). The Kenticha pegmatite deposit in Ethiopia contains tantalite and lithium minerals (lepidolite and spodumene). Tantalum, niobium, beryllium, lithium, cesium, and rubidium are among the rare metals that are connected with the pegmatites (Tadesse 2001). Spodumene is colorless, transparent, gray, greenish-gray, yellowish-gray, pinkish, yellowish-greenish, light violet-pink, and very rarely blue. The spodumene has a hardness between 6.5–7.0 on the Mohs hardness scale (Ostroushko 1962). The primary silicate mineral that contains lithium is spodumene (Tadesse et al. 2019). Designing comminution processes requires that the power requirements of crushing and grinding operations be taken into account (Menéndez et al. 2005). Work index of spodumene ore at southern Ethiopian pegmatite ore deposit known as Kenticha and any other country not studied previously by any method. The determination of the work index of Spodumene from Kenticha Ore, Southern Ethiopia, is carried out using Modified Bond Index. The host rock of Kenticha spodumene ore is pegmatite. Granite is considered a reference sample because it has a known work index and is similar to pegmatite in composition. The Kenticha granite pegmatite field is characterized by monomineralic quartz, spodumene, and muscovite pegmatites, along with blocky microcline and muscovite-albite granite. (Mohammedyasin 2017). The parameter obtained in this work is very significant in Kenticha spodumene plant design. It will also provide important information for future processing plants of the spodumene ore deposit, and the end result of this study is a good resource for researchers as well as for other explorers.

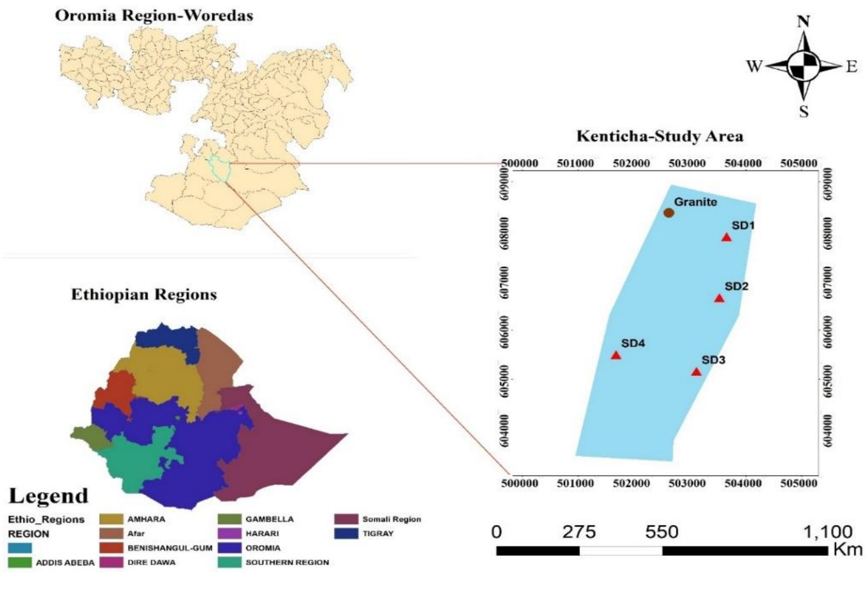


Fig. 1. Location map of Kenticha study area

2. MATERIALS AND METHODS

Samples of spodumene and granite were collected from the Kenticha ore deposit, found in southern Ethiopia, 600 km from the capital, Addis Ababa. Random sampling was used to collect spodumene ore samples from the Kenticha to ensure a representative and unbiased assessment of the deposit characteristics. Four samples, each weighing approximately 2 kg, along with 1 kg of granite from an outcrop. The exact coordinates point for each sample are as follows: SD1 (503660E, 607888N), SD2 (503532E, 606654N), SD3 (503120E, 605161N), SD4 (501679E, 605496N), and the granite sample (502624E, 608373N).

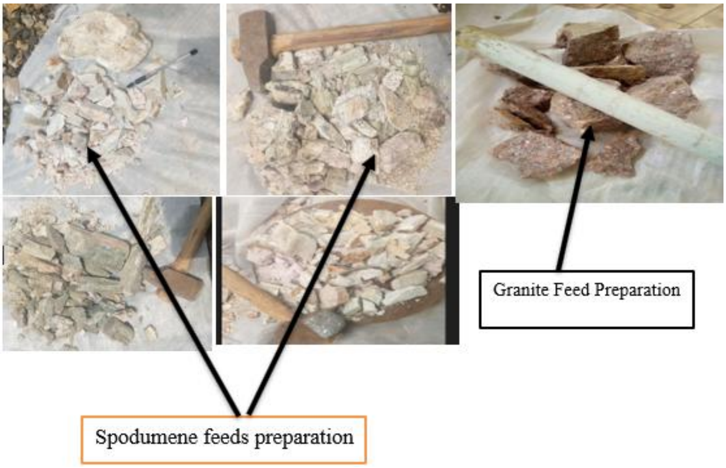


Fig. 2. Samples preparation to feed into laboratory jaw crusher

To improve the methodological rigor, it is essential to standardizing the experimental setup involves maintaining a stable circulating load, employing a standardized closing sieve size, and accurately measuring the energy input during grinding, as the standard Bond test requires feed material to pass under a 3350-micrometer feed. To validate the Modified Bond Work Index (MBWI) method, researchers must compare its outcomes with those from a standard Bond grindability test to ensure consistency and dependability. Researchers consult research papers and publications that have validated similar MBWI methods for insights and best practices. The granite work index was obtained from the literature, while the values of 80% passing product (P80) and 80% passing feed (F80t) for spodumene feed and granite were obtained using Gaudian–Schumann's expression (Alabi et al. 2015; Wills and Napier-Mum 2006). Determination of Work Index of spodumene samples from kenticha using Berry and Bruce (Modified Bond Index) (Wills and Napier-Mum, 2006). First, the authors measured the weight of each sieve, then arranged them in a stack with the largest aperture sieve at the top and a collection pan at the bottom 2 kg (2000 gram) (divided into four equal parts with 500 g) and 500 g of spodumene for chemical analysis using Atomic Absorption Spectroscopy and granite (500 g) were crushed in a laboratory jaw crusher. The Kenticha spodumene ore and granite were sieved for 5 minutes. The weights of the Kenticha spodumene and granite in each size fraction were recorded as “feed” values. Ground feed for 1 hour (feed 1 for 20 minutes, feed 2 for 15 minutes, feed 3 for 10 minutes, and feed 4 for 5 minutes) and reference sample granite for 10 minutes. To determine the optimal times for assessing the Work Index, authors should ensure that each test is conducted under consistent, controlled conditions and that data is collected accurately. Use the same type of ore i.e., spodumene with a consistent particle size distribution for each test. Since the material is expected to have relatively stable properties, short intervals between tests might suffice. Repeat the test multiple times with different grinding times for the test ore to enhance accuracy.

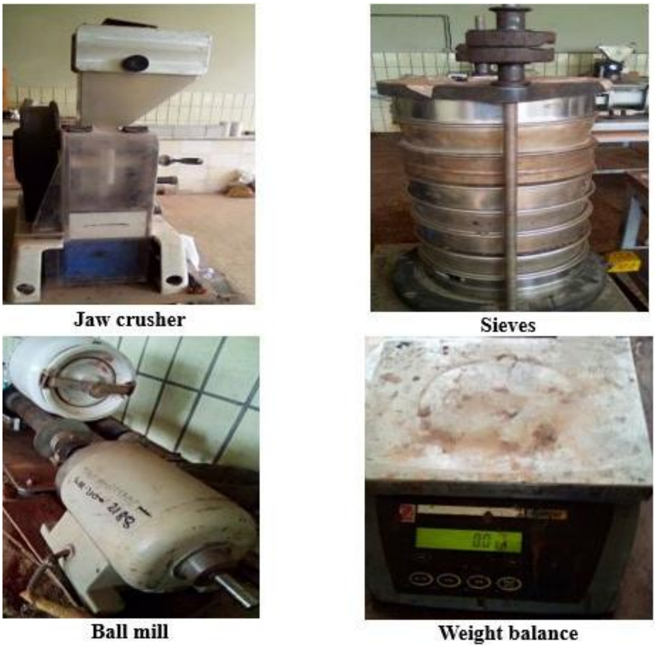


Fig. 3. Equipments used for laboratory work

3. RESULTS AND DISCUSSION

3.1. SPODUMENE ORE ANALYSIS

The chemical analysis results of the kenticha spodumene in pegmatite are presented in Table 1. The analysis was carried out using Atomic Absorption Spectroscopy (AAS).

Chemical analysis for lithium ore spodumene involves the following steps: To make this determination, the authors did four measurements of the analyte (spodumene ore) sample chemical compositions in one preparation, which means the samples are crushed and ground to –200 mesh (all particles that pass through 200 mesh). Each sample weighs 0.2 grams of the spodumene sample. The RSD, shown as a percentage, indicates the extent to which data points diverge from the average value. The larger relative standard deviation for one oxide compared to another in an ore sample generally indicates

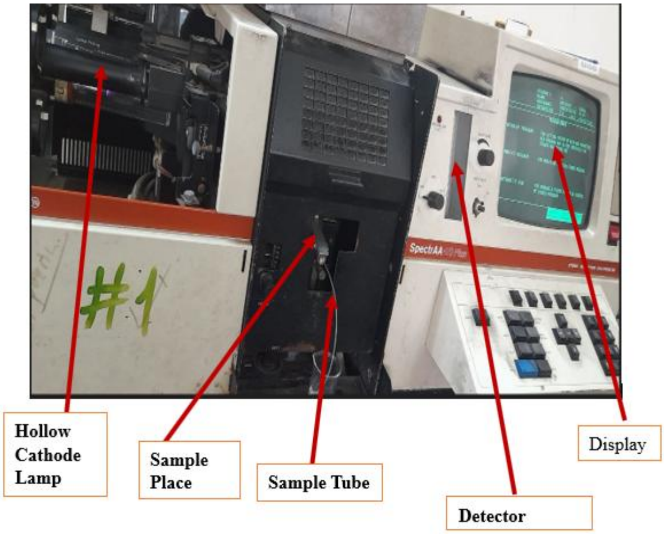


Fig. 4. Atomic Absorption Spectroscopy Instrument

Table1. Chemical Constituents (oxides) of the Test Ore (spodumene) (wt. %)

Field no.	SiO_2 [%]	Al_2O_3 [%]	CaO [%]	MgO [%]	Na_2O [%]	K_2O [%]	Fe_2O_3 [%]	Li_2O [%]	LOI
SD-01	66.25	21.45	0.65	0.68	5.25	1.5	0.32	3.21	3.26
SD-02	65.12	22.13	0.62	0.67	4.25	1.31	0.51	2.04	6.05
SD-03	66.25	22.13	0.53	0.56	3.98	1.1	0.89	1.86	5.23
SD-04	69.28	21.69	0.29	0.32	1.36	0.47	0.69	1.88	2.56
Minimum	65.12	21.45	0.29	0.32	1.36	0.47	0.32	1.86	2.56
Maximum	69.28	22.13	0.65	0.68	5.25	1.5	0.89	3.21	6.05
Average	66.73	21.85	0.52	0.56	3.71	1.10	0.60	2.25	4.28
Standard deviation	1.55	0.29	0.14	0.15	1.44	0.39	0.21	0.56	1.42
Relative standard deviation	2.32	1.34	27.05	26.01	38.73	35.40	35.08	24.92	33.15

greater variability in the concentration of that specific oxide within the ore body. Higher RSD in chemical composition 38.7% for Na_2O implies that the concentration of that sodium oxide varies more significantly from one location to another within the Kenticha spodumene ore body than the concentration of the other oxide. In summary, a higher relative standard deviation of Na_2O indicates a greater degree of heterogeneity or variability in the concentration of sodium oxide within the Kenticha spodumene ore body. The differences in sodium oxide levels within spodumene ore result from a factor, including the ore's geological formation, its history of alteration, Factors such as the presence of other minerals, hydrothermal processes and weathering.

3.2. SIEVE ANALYSIS OF SPODUMENE AND GRANITE AS FEED INTO THE BALL MILL

The Gaudian–Schumann expression can be represented as follows: size 1 is the size determined by the sieve analysis results, and size 2 is the 80% passing size (Alabi et al. 2015; Wills and Napier-Mum 2006):

$$\text{size}_2 = \frac{(\text{percentage passing size}_2)^2}{(\text{percentage passing size}_1)^2} \times \text{size}_1 \tag{1}$$

compare with most commonly used Gaudian–Schumann expression (given below) to the version.

$$P = 100 * \left(\frac{x}{\kappa}\right) a. \tag{2}$$

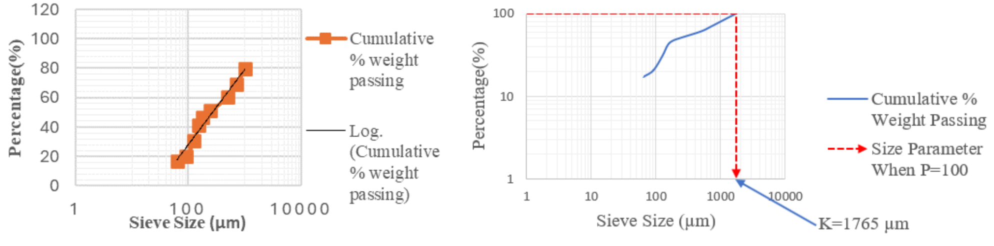
P = mass passing (%), x = particle size in microns, κ = size parameter, i.e., size when P = 100 and a = distribution parameter. The authors have been able to find the following for both spodumene and reference granite: F_{80r} (80% of feed of reference sample), F_{80t1} (80% of feed 1 test ore passes), F_{80t2} (80% of feed 2 test ore passes), F_{80t3} (80% of feed 3 test ore passes), and F_{80t4} (80% of feed 4 test ore passes).

Table 2. Sieve result feed 1 sample of Kenticha spodumene ore

Size [µm]	Ret. weight [g]	Ret. % weight	Cumulative % retained	Cumulative % passing
+1000	102.15	20.43	20.43	79.57
−1000 + 710	51.55	10.31	30.74	69.26
−710 + 500	42.95	8.59	39.33	60.67
−500 + 250	47.85	9.57	48.90	51.1
−250 + 180	22.30	4.46	53.36	46.64
−180 + 150	27.10	5.42	58.78	41.22
−150 + 125	52.00	10.40	69.18	30.82
−125 + 90	51.95	10.39	79.57	20.43

Table 2 continued

−90 + 63	17.10	3.42	82.99	17.01
−63	85.05	17.01	100.00	0.00
Total	500.00 g	100%		

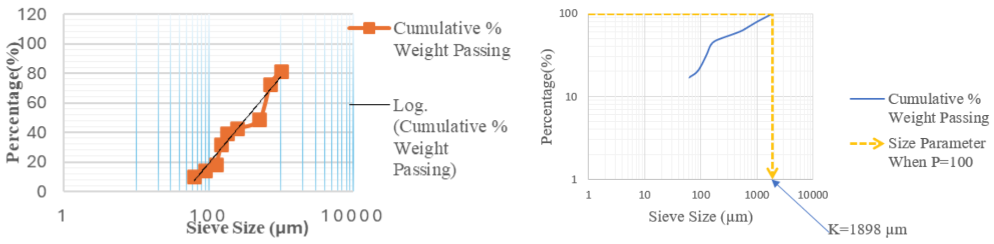


(a) (b)

Fig. 5. Semi logarithm (a) and log-log (b) plot of the cumulative percentage weight retained and passing against sieve size of the feed 1 to ball mill for test ore (spodumene)

Table 3. Sieve result of feed 2 sample of Kenticha spodumene ore

Size [μm]	Weight retained [g]	Ret. % weight	Cumulative % retained	Cumulative % passing
+1000	92.85	18.57	18.57	81.43
−1000 + 710	44.75	8.95	27.52	72.48
−710 + 500	119.00	23.80	51.32	48.68
−500 + 250	30.80	6.16	57.48	42.52
−250 + 180	16.65	3.33	60.81	39.19
−180 + 150	37.10	7.42	68.23	31.77
−150 + 125	66.50	13.30	81.53	18.47
−125 + 90	20.15	4.03	85.56	14.44
−90 + 63	21.65	4.33	89.89	10.11
−63	50.55	10.11	100.00	0.00
Total	500.00 g	100%		



(a) (b)

Fig. 6. Semi logarithm (a) and log-log (b) graph for feed 2 to ball mill for test ore (spodumene)

Table 4. Sieve result of feed 3 of Kenticha spodumene ore

Size [μm]	Mass retained [g]	Ret. % mass/weight	Cumulative % ret.	Cumulative % pass.
+1000	104.35	20.87	20.87	79.13
−1000 + 710	40.50	8.10	28.97	71.03
−710 + 500	45.35	9.07	38.04	61.96
−500 + 250	42.15	8.43	46.47	53.53
−250 + 180	20.30	4.06	50.53	49.47
−180 + 150	26.90	5.38	55.91	44.09
−150 + 125	37.00	7.40	63.31	36.69
−125 + 90	26.35	5.27	68.58	31.42
−90 + 63	60.30	12.06	80.64	19.36
−63	96.80	19.36	100.00	0.00
Total	500.00 g	100%		

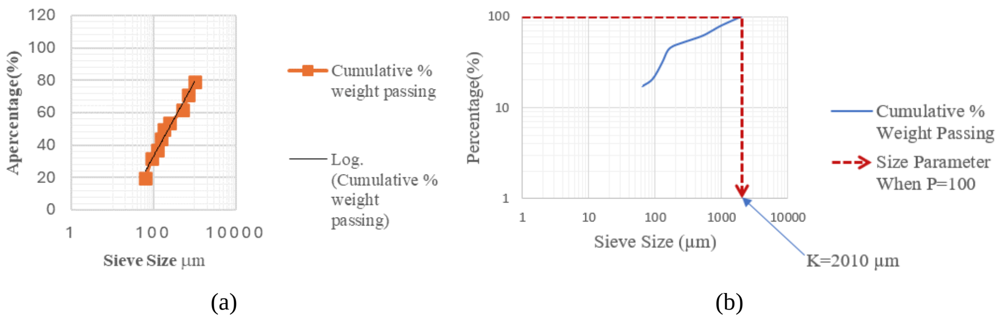
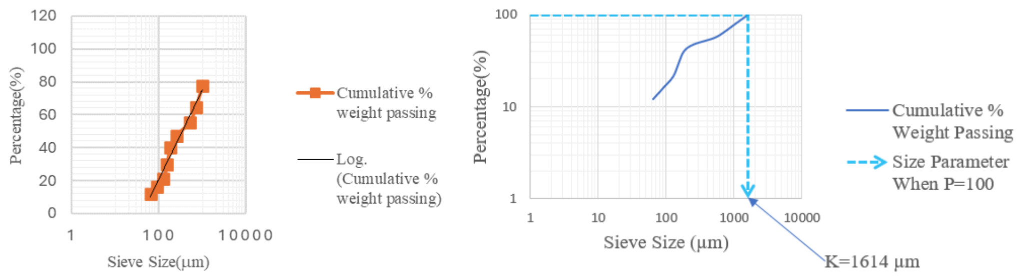


Fig. 7. Semi logarithm (a) and log-log (b) graph for feed 3 to ball mill for test ore (spodumene)

Table 5. Sieve result of feed 4 sample of Kenticha spodumene ore

Sieve size (μm)	Weight/mass Ret. [g]	% weight/mass ret.	Cumulative % ret.	Cumulative % pass.
+1000	111.35	22.27	22.27	77.73
−1000 + 710	65.60	13.12	35.39	64.61
−710 + 500	45.35	9.07	44.46	55.54
−500 + 250	41.15	8.23	52.69	47.31
−250 + 180	36.90	7.38	60.07	39.93
−180 + 150	51.70	10.34	70.41	29.59
−150 + 125	41.50	8.30	78.71	21.29
−125 + 90	25.85	5.17	83.88	16.12
−90 + 63	20.30	4.06	87.94	12.06
−63	60.30	12.06	100.00	0.00
Total	500.00g	100%		

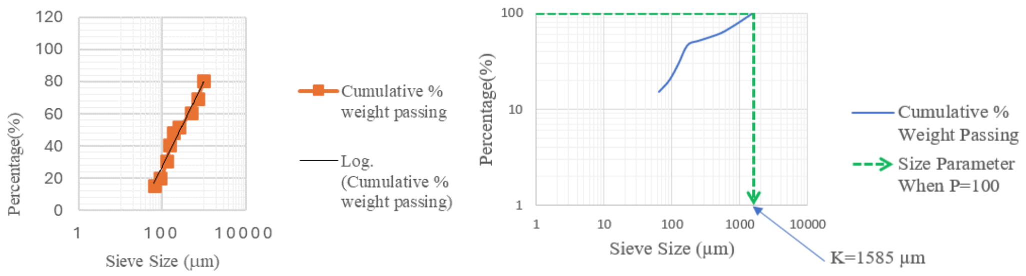


(a) (b)

Fig. 8. Semi logarithm (a) and log-log (b) plot graph for feed 4 to ball mill for test ore (spodumene)

Table 6. Sieve result of sample granite (feed to the ball mill)

Size [μm]	Weight mass ret. [g]	% mass ret.	Cumulative. % ret.	Cumulative. % pass.
+1000	97.15	19.43	19.43	80.57
−1000 + 710	56.55	11.31	30.74	69.26
−710 + 500	42.95	8.59	39.33	60.67
−500 + 250	45.95	9.19	48.52	51.48
−250 + 180	16.75	3.35	51.87	48.13
−180 + 150	37.20	7.44	59.31	40.69
−150 + 125	52.00	10.40	69.71	30.29
−125 + 90	51.95	10.39	80.10	19.90
−90 + 63	24.30	4.86	84.96	15.04
−63	75.20	15.04	100.00	0.00
Total	500.00 g	100%		



(a) (b)

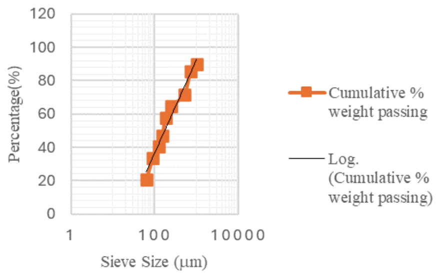
Fig. 9. Semi logarithm (a) and log-log (b) plot graph feed to ball mill for reference sample (granite)

3.3. TEST ORE (SPODUMENE)/REFERENCE (GRANITE) OUTPUT (PRODUCT)

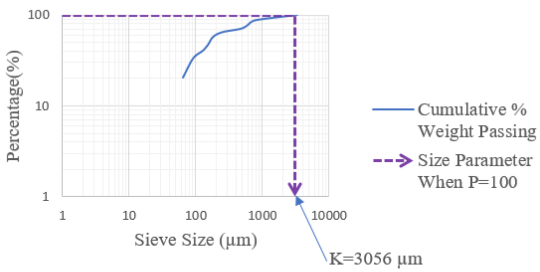
The authors have been able to find the following for both test ore and reference sample (granite): P_{80r} (80% of discharge reference sample passes), P_{80t1} (80% of discharge feed 1 test ore passes), P_{80t2} (80% of discharge feed 2 test ore passes), P_{80t3} (80% of discharge feed 3 test ore passes), and P_{80t4} (80% of discharge feed 4 test ore passes).

Table 7. Sieve analysis of spodumene ore (product 1 of feed 1)

Sieve (micro)	Retained weight/mass [g]	% weight/mass retained	Ret. cumulative %	Passing cumulative %
+1000	50.00	10.00	10.00	90.00
−1000 + 710	22.20	4.44	14.44	85.56
−710 + 500	69.90	13.98	28.42	71.58
−500 + 250	33.60	6.72	35.14	64.86
−250 + 180	36.20	7.24	42.38	57.62
−180 + 150	52.85	10.57	52.95	47.05
−150 + 125	33.05	6.61	59.56	40.44
−125 + 90	34.25	6.85	66.41	33.59
−90 + 63	64.85	12.97	79.38	20.62
−63	103.10	20.62	100.00	0.00
Total	500.00 g	100%		



(a)



(b)

Fig. 10. Semi logarithm (a) and log-log (b) graph Product1 from Ball Mill for Test Ore (spodumene)

Table 8. Sieve analysis of spodumene ore (product of feed 2) from the ball mill

Size (micro)	Mass ret. [g]	% mass ret.	Cumulative % ret.	Cumulative % pass.
+1000	50.00	10.00	10.00	90.00
−1000 + 710	27.20	5.44	15.44	84.56

Table 10 continued

−710 + 500	69.90	13.98	29.42	70.58
−500 + 250	48.60	9.72	39.14	60.86
−250 + 180	53.10	10.62	49.72	50.28
−180 + 150	62.85	12.57	62.33	37.67
−150 + 125	40.50	8.10	70.43	29.57
−125 + 90	29.25	5.85	76.28	23.72
−90 + 63	24.05	4.81	81.09	18.91
−63	94.55	18.91	100.00	0.00
Total	500.00g	100%		

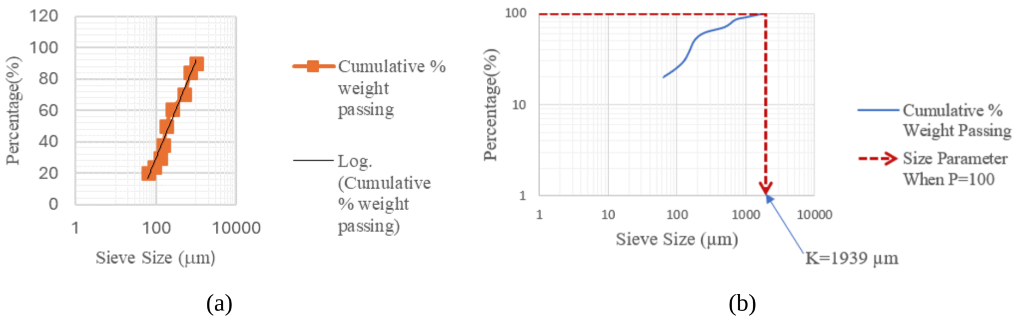
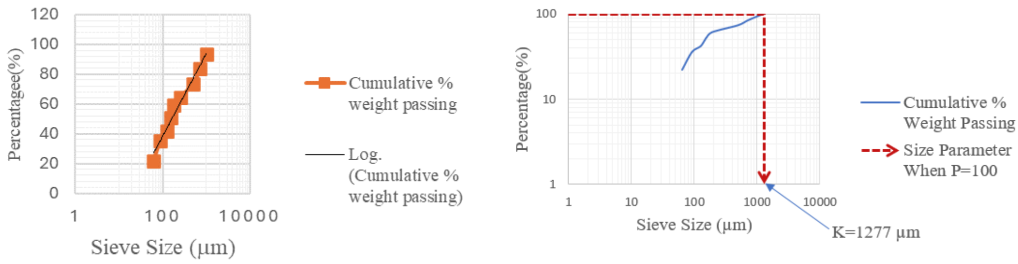


Fig. 11. Semi logarithm (a) and log-log (b) graph product 2 from ball mill for test ore (spodumene)

Table 9. Sieve analysis of spodumene ore (product of feed 3)

Size (micro)	Mass ret. [g]	% mass ret.	Cumulative % ret.	Cumulative % pass.
+1000	33.90	6.78	6.78	93.22
−1000 + 710	47.85	9.57	16.35	83.65
−710 + 500	51.00	10.20	26.55	73.45
−500 + 250	45.15	9.03	35.58	64.42
−250 + 180	25.30	5.06	40.64	59.36
−180 + 150	41.90	8.38	49.02	50.98
−150 + 125	47.00	9.40	58.42	41.58
−125 + 90	31.95	6.39	64.81	35.19
−90 + 63	66.75	13.35	78.16	21.84
−63	109.20	21.84	100.00	0.00
Total	500.00g	100%		

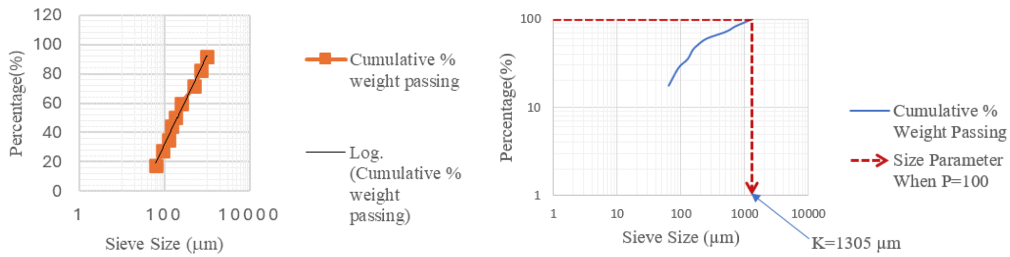


(a) (b)

Fig. 12. Semi logarithm (a) and log-log (b) graph discharge for feed 3 from ball mill for test ore (spodumene)

Table 10. Sieve analysis of spodumene ore as product of feed 4

Size (micro)	Mass ret. [g]	% mass ret.	Cumulative % ret.	Cumulative % pass.
+1000	40.55	8.11	8.11	91.89
−1000 + 710	45.80	9.16	17.27	82.73
−710 + 500	55.60	11.12	28.39	71.61
−500 + 250	58.85	11.77	40.16	59.84
−250 + 180	46.75	9.35	49.51	50.49
−180 + 150	31.20	6.24	55.75	44.25
−150 + 125	46.50	9.30	65.05	34.95
−125 + 90	35.85	7.17	72.22	27.78
−90 + 63	51.60	10.32	82.54	17.46
−63	87.30	17.46	100.00	0.00
Total	500.00 g	100%		



(a) (b)

Fig. 13. Semi logarithm (a) and log-log (b) graph discharge feed 4 from ball mill for test ore (spodumene)

Table 11. Sieve analysis of sample of granite (product)

Size (micro)	Mass ret. [g]	% mass ret.	Cumulative % ret.	Cumulative % pass.
+1000	40.00	8.00	8.00	92.00
−1000 + 710	50.75	10.15	18.15	81.85
−710 + 500	25.35	5.07	23.22	76.78
−500 + 250	52.55	10.51	33.73	66.27
−250 + 180	30.15	6.03	39.76	60.24
−180 + 150	58.15	11.63	51.39	48.61
−150 + 125	48.80	9.76	61.15	38.85
−125 + 90	39.80	7.96	69.11	30.89
−90 + 63	56.30	11.26	80.37	19.63
−63	98.15	19.63	100.00	0.00
Total	500.00 g	100%		

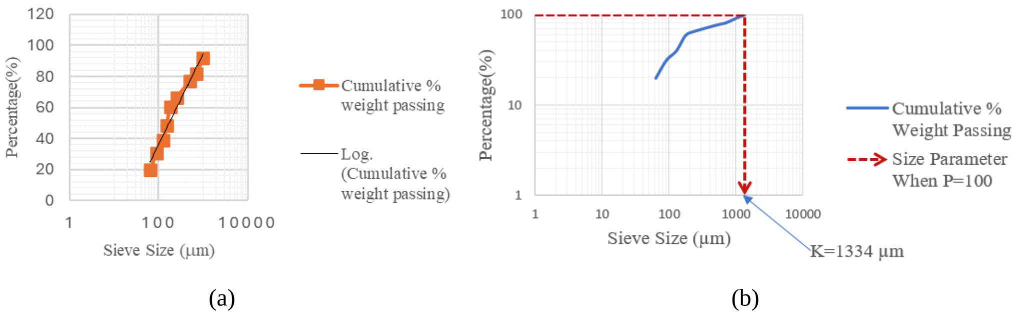


Fig. 14. Semi logarithm (a) and log-log (b) graph product from ball mill for reference sample (granite)

3.4. CALCULATION RESULT OF KENTICHA SPODUMENE

Using Bond's equation (Eq. (3)) and the work index reference sample granite is 15.13 kWh/ton (Wills and Napier-Mum 2006).

$$W_{it} = W_{ir}\left(\frac{10}{\sqrt{P_{80r}}} - \frac{10}{\sqrt{F_{80r}}}\right) : \left(\frac{10}{\sqrt{P_{80t}}} - \frac{10}{\sqrt{F_{90t}}}\right), \tag{3}$$

when compare with most commonly used Gaudian–Schumann expression (in Eq. (2)) above and values of *k* from Figs. 5–14 log-log plots at *b* values for sizes and average work index is approximately the same in range.

$$a = \left(\frac{\log(y_2) - \log(y_1)}{\log(x_2) - \log(x_1)}\right), \tag{4}$$

when a is distribution parameter or slope of the log-log plot P vs. x. Use equations (5) and (6) to compare values as follows. The value for F_{80t1} (80% of feed 1 test ore passes) was obtained using the output from Table 2.

$$X\ \mu\text{m} = \frac{\left(\frac{80}{100}\right)^2}{\left(\frac{79.57}{100}\right)^2} \times 1000\ \mu\text{m} = 1010.83\ \mu\text{m at } 80\%, \tag{5}$$

$$a = \left(\frac{\log(79.57) - \log(69.26)}{\log(1000) - \log(710)}\right) = 0.40 \quad 80 = 100 * \left(\frac{X}{1765}\right)^{0.40} \quad X = 1010.34\ \mu\text{m}. \tag{6}$$

Table 12. comparing value obtained using Eqs. (5) and (6)

Tests	P_{80} (80% of passes of tests) μm using Eq. (5)	a (distribution parameter)	P_{80} (80% of passes of tests) μm using Eq. (6)
F_{80t1} (Table 2)	1010.83	0.40	1010.43
F_{80t2} (Table 3)	965.18	0.33	965.22
F_{80t3} (Table 4)	1022.11	0.33	1022.18
F_{80t4} (Table 5)	1059.26	0.53	1059.38
F_{80r} (Table 6)	985.91	0.47	985.91
P_{80t1}(Table 7)	620.72	0.14	620.78
P_{80t2} (Table 8)	635.49	0.20	635.37
P_{80t3} (Table 9)	649.39	0.33	649.41
P_{80t4} (Table 10)	663.91	0.33	663.67
P_{80r} (Table 11)	678.26	0.33	678.40

P_{80r} (μm) = 678.26 μm, F_{80r} (μm) = 985.90 μm, P_{80t1} (μm) = 620.72 μm, and F_{80t1} (μm) = 1010.83 μm

$$W_{it1} = 15.13\, kWh/ton \left(\frac{10}{\sqrt{678.26}} - \frac{10}{\sqrt{985.90}}\right) : \left(\frac{10}{\sqrt{620.72}} - \frac{10}{\sqrt{1010.83}}\right) \tag{7}$$

15.13 kWh/ton × $\frac{0.06}{0,086}$ = 10.5558 kWh/ton. when compare with value for size obtained Gaudian–Schumann expression (Eq. (6)). W_{it1} = 10.4705 kWh/ton. Use Eq. ((7)) for all by using corresponding value for all feeds. W_{it2} = 11.3475 kWh/ton. when compare with value for size obtained Gaudian–Schumann expression (Eq. (6)). W_{it2} = 11.210 kWh/ton. W_{it3} = 11.4911 kWh/ton when compare with value for size obtained Gaudian–Schumann expression (Eq. (6)).

W_{it3} = 11.4045 kWh/ton. W_{it4} = 12.171 kWh/ton. when compare with value for size obtained Gaudian–Schumann expression (Eq. (6)). W_{it4} = 11.5461 kWh/ton.

$$W\text{test(average)} = (w_{it1} + w_{it2} + w_{it3} + w_{it4}) : 4, \quad (8)$$

Wt(av) = (10.555 + 11.347 +11.491 + 12.171) kWh/ton : 4 = 11.391 kWh/ton.

Based on the above results and discussion, the authors have determined that the average total work index of the Kenticha spodumene ore sample is 11.391 kWh/ton. This value compares the work index of spodumene ore, which has been determined in the literature to be between 10.4 and 11.5 kWh/ton (Michaud 2022).

4. CONCLUSION

The work index of Kenticha pegmatite spodumene ore was determined by the Berry and Bruce method, and the following conclusions were drawn: The results from Tables 2–11 and Figures 5–14 graphical distributions for sample (granite) and test ore (spodumene) show 80% passing for all four feeds and four product sieve size fractions for the reference sample (granite) and the spodumene ore samples. The particle size fraction 80% passing for all feeds (feed 1, feed 2, feed 3, feed 4) and the products (product 1, product 2, product 3, product 4) of the spodumene ore sample was found to be (1010.83, 965.18, 1022.11,1059.26) µm and (620.72, 635.49, 649.39, 663.91) µm, respectively. The work index for feed 1, feed 2, feed 3, and feed 4 of test ore spodumene is 10.555, 11.347, 11.491, and 12.171 kWh/ton, and the average work index for kenticha spodumene ore is 11.391 kWh/ton at laboratory scale. This means that 11.391 kWh/ton of energy is needed to comminute kenticha spodumene ore from an infinite feed size to 80% passing 100 µm. When compared to the work index of spodumene ore, the result obtained lies favorably within the work indexes of 10.4–11.5 kWh/ton for spodumene ore cited in the literature. This will further ensure a proper choice of mining equipment in future mining progress in the area, which will enable us to save energy and take cost-effective measures. The parameters obtained in this project are very significant in kenticha spodumene plant design.

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