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MSC IN MINERAL ENGINEERING MASTER'S PROGRAM A PROJECT ON THE

**Analyzing the Effect of Operational Parameters on the
Breakage Mechanisms of Spodumene Mineral to Optimize
the Comminution Processes of Lithium Bearing Pegmatite
in Kenticha, Ethiopia**

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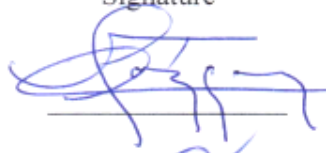
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Some Abbreviations used which were not explained

KWh/t - Killo Watt Hour per Tone

Albt - the mineral Albite

RPM - Rotation per minute

Qtz - the mineral Quartz

Spd - the Ore Spodmene

Mcln- the mineral Microcline

Bt - the mineral Biotite

Mst - the mineral Muscovite

Abstract

This study is aimed to investigate the optimal operational conditions for breaking down the Kenticha, Ethiopia Li-pegmatite, which contains lithium minerals, particularly spodumene. The goal is to produce high-quality spodumene concentrate by achieving the desired particle size, particle distribution, which are crucial for efficient separation during the physical separation and subsequent froth flotation steps. To achieve this, one sample from Kenticha Li-pegmatite replicated four times were characterized using X-ray diffraction (XRD) and atomic absorption spectroscopy (AAS) techniques for mineralogical and geochemical analysis respectively. XRD analysis confirmed that the ore was predominantly composed of spodumene, with minor amounts of quartz, mica and feldspar. AAS analysis showed that the ore contained a moderately high level of lithium (approximately 2.5%) as well as other trace elements such as iron, and very low amount manganese and phosphorus. The results indicated that the ore had the potential to be a valuable source of lithium for industrial purposes. The sample then were crushed using a Laboratory Jaw Crusher in primary step and the study was conducted for different conditions parameters of grinding as a secondary step using a Laboratory Ball Mill. Optimal breakage mechanism was determined to achieve the desired spodumene concentrate. The results showed that the optimal conditions under the experimental analysis identified as milling power: 41 W, amount of feed: 250 g and the milling speed: 500 rpm, could produce narrow size distribution and the desired particle size for high spodumene concentration. This research has significant implications in the field of lithium mineral processing, providing important insights into the operational parameters that can achieve high-quality spodumene concentrate.

Key Words: Lithium minerals, comminution, operational parameters, particle size distribution, power consumption

1. INTRODUCTION

1.1. Background of Lithium Minerals

Lithium is found in a number of minerals like spodumene, lepidolite, and also commonly associated in the form of lithium carbonate with potash in evaporite deposits or salt lakes. Lithium is a highly reactive metal, only occurs in nature combined with other elements in a variety of minerals (Table 1). Lithium deposits in the world are generally grouped into three types: (1) brines and related evaporite deposits make up 66% of the world lithium resource, (2) pegmatites (26%), and (3) Sedimentary rocks (8%) (Paul and Pablo, 2010).

Table 1. Main lithium minerals (Brooks, 2020)

Mineral	Formula	Remarks
Spodumene	$\text{LiAl Si}_2\text{O}_6$	A member of the pyroxene group
Holmquistite	$\text{Li}_2(\text{Mg,Fe})_3\text{Al}_2\text{Si}_8\text{O}_{22}(\text{OH})_2$	A member of the amphibole group
Lepidolite)	$\text{K}(\text{Li,Al})_3(\text{Si,Al})_4\text{O}_{10}(\text{F,OH})_2$	A member of the mica group
Polyolithionite	$\text{KLi}_2\text{AlSi}_4\text{O}_{10}(\text{F,OH})_2$	(phylosilicate
Zinnwaldite	–	Another member of the mica group
Hectorite	$\text{Na}_{0.3}(\text{Mg,Li})_3\text{Si}_4\text{O}_{10}(\text{OH})_2$	No longer recognized as a distinct mineral
Cookeite	$(\text{LiAl}_2)\text{Al}_2(\text{AlSi}_3\text{O}_{10})(\text{OH})_8$	
Petalite	$\text{LiAlSi}_4\text{O}_{10}$	A clay mineral, related to
Eucryptite	$\text{Li}(\text{AlSiO}_4)$	montmorillonite
Amblygonite	$(\text{LiNa})\text{Al}(\text{PO}_4)(\text{F,OH})$	Chlorite group
Lithiophyllite	$\text{LiMn}(\text{PO}_4)$	Another phyllosilicate (sheet silicate)
Triphyllite)	$\text{LiFe}(\text{PO}_4)$	A nesosilicate (like olivine) but relate
Elbaite	$\text{Na}(\text{Li}_{1.5}\text{Al}_{1.5})\text{Al}_6\text{Si}_6\text{O}_{18}(\text{BO}_3)_3(\text{OH})_4$	to phenakite (Be_2SiO_4)
Jadarite	$\text{NaSiB}_3\text{O}_7\text{OH}$	Phosphate
		Phosphate
		Tourmaline group
		A recently discovered Li mineral

From these, an important group mimics the common rock-forming minerals, being in the form of polymerized SiO_4^{4-} groups: rings, chains, bands and sheets which are held together by

interstitial lithium and aluminum ions and thus, enstatite is a form of pyroxene (and a common rock-forming mineral) and has the formula MgSiO_3 ($=\text{Mg}_2\text{Si}_2\text{O}_6$), while spodumene has $\text{Li}^+ + \text{Al}^{3+}$ in place of the 2Mg^{2+} ($\text{LiAlSi}_2\text{O}_6$) (Brooks, 2020). Lithiophyllite and triphyllite are end-members of a solid solution series, that is, there is a continuous change of composition between them (Brooks, 2020).

Spodumene is a kind of pyroxene that has a basic structure made up of chains of SiO_4 tetrahedral. These chains are built up by each tetrahedron sharing an oxygen ion with its neighbor, and they are held together by interstitial Li^+ and Al^{3+} ions. This structure results in orthorhombic or monoclinic crystal symmetry and two perfect cleavages at almost right angles to each other. Although spodumene is typically monoclinic (α -spodumene), it can invert to a tetragonal form (β -spodumene) above 900°C . Crystals of spodumene typically have striations (Brooks, 2020).

The naturally occurring α -phase of spodumene is highly refractory, so it is typically calcined (i.e., thermally treated at temperatures over 900°C) to convert it to the β -phase (Reuben et al, 1950). The calcination process makes spodumene more brittle and reactive for acid roasting. This is because α -spodumene crystals have a 30% lower volume than β -spodumene crystals (Muhammad, 2022).

Lithium is an essential element for many applications, including rechargeable batteries, ceramics, glass, lubricants, and pharmaceuticals. The increasing demand for lithium-ion batteries has led to a higher demand for lithium minerals. However, the global supply of lithium minerals is limited and mainly found in a few countries, such as Chile, Australia, and China. The recognition of the adverse impacts of climate change and the importance of mitigating CO_2 emissions has resulted in the development of alternative vehicles with lower CO_2 emissions than conventional internal combustion engine vehicles. Vehicle electrification is one strategy being pursued, with key technologies including hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and battery electric vehicles (BEVs). Several studies have shown that electric vehicles have significantly lower life cycle greenhouse gas emissions than internal combustion engine vehicles, and even greater

reductions are possible through greater penetration of renewable electricity sources into the grid. Major automobile companies are developing electrified vehicles and considering lithium-based batteries to power them (Paul and Pablo, 2010). Therefore, the exploration and exploitation of lithium minerals in other regions, such as Ethiopia, are crucial for meeting the current and future demand for this crucial element. Lithium is a metal with increasing demand on the global market, mainly for its application in lithium-ion batteries for electric vehicles. Ethiopia has potential for lithium resources related to pegmatites in Kenticha and to rift-bound brine deposits, but they are not well-investigated.

1.2. Problem Statement

During mineral comminution, breakage plays a crucial role in liberating mineral phases from each other. The mode of breakage is influenced by various factors, including pre-treatment, process, and material type, as well as particle properties such as size, shape, and texture. Breakage mechanism can impact the degree of liberation, which in turn affects downstream separation processes. In crushing operations, compression and impact forces are primarily used, while attrition forces are dominant in grinding. Different equipment and materials activate each type of fragmentation mechanism to a varying extent, yielding ground material with different characteristics.

Mineral exploration in Ethiopia has resulted in the discovery of Lithium deposits in Kenticha (Oberthür, 2009, Tadesse and Zerihun, 1996), the Danakil Depression, and certain areas of the main Ethiopian Rift lakes (Bekele and Schmerold, 2020). These deposits are of great importance to the country's future due to the potential of this valuable element. Although researchers have investigated the mineralogy and chemical composition of these deposits, further investigation into how the mineral behaves during processing, starting with beneficiation, is necessary. Therefore, the research problem of this thesis is to establish the foundations of how the mineral behaves when subjected to the comminution process in terms of particle size distribution and power consumption.

1.3. General Objective

The aim of this study is **to investigate the breakage mechanism of ball mill during the comminution processing of Lithium minerals from the Kenticha mine, Ethiopia.**

1.3. 1. Specific Objectives

1. To establish the influence on the particle size distribution and power consumption of the mill by varying the feed amount and rotational speed of the mill.
2. To explore the optimal conditions for efficient grinding and improved lithium production from the Kenticha mine.
3. To improve the analytical and technical to investigate the complex interactions between milling parameters, breakage mechanism, and product quality Lithium-bearing ores in Kenticha, Ethiopia.
4. To identify the potential to enhance our understanding of the complex interactions between milling parameters, breakage mechanism, and product of Lithium-bearing ores from Kenticha, Ethiopia.

1.4. Scope

This research is important for the mineral processing industry as it highlights the significance of comminution in achieving desired product outcomes. By understanding the factors that influence comminution behavior such as mineralogy, feed amount, and rotational speed in comminution of Lithium-bearing ores from Kenticha, Ethiopia, the industry can optimize the design and operation of crushing and grinding circuits, as well as pre-treatment technologies. This, in turn, can lead to improvements in energy efficiency, reduced operational costs, and improved product quality.

This study contributes to the understanding of the comminution process and the importance of achieving the desired particle size and distribution for further optimum extraction. It emphasizes the need for careful consideration of operational parameters for future decisions related to the exploitation of Lithium-bearing ores from Kenticha, Ethiopia. By optimizing comminution behavior, the mineral processing industry can achieve efficient and effective processing of ores, leading to improved product outcomes.

2. LITERATURE REVIEW: COMMUNITION Li-PEGMATITE (SPODUMENE)

2.1 Introduction

As technology advances in the 21st century, the demand for lithium is increasing. [Gurial & Juan \(2018\)](#) describe two types of lithium deposits: minerals and brine. The most significant Li-bearing mineral is Spodumene, which is extracted from Pegmatite deposits. Other sources such as petalite and lepidolite are less economically important. Future sources of lithium may include hectorite and jadeite deposits. Lithium can also be found in brine from continental, geothermal, and oilfield sources. Although lithium is found in igneous rocks, it is in very low concentrations, and the largest amounts of lithium-containing minerals are found in granitic Pegmatite. Spodumene contains the highest theoretical Li_2O content of 8.03% and is considered the most important lithium ore mineral.

2.1.1.Lithium deposits in Ethiopia

Spodumene is a type of monoclinic pyroxene that has a single-chain structure. It is a tabular hard rock that cannot be dissolved by dilute acids. It is commonly found in Pegmatite deposits along with other silicate minerals like feldspar, micas, and quartz. It contains around 8% Li_2O , making it one of the most abundant lithium-bearing minerals in nature. The name "Spodumene" comes from a Greek word that means "burnt to ashes," which refers to its typical color of Grey, although various other colors can also be found.

The Kenticha pegmatite is a type of rare element Pegmatite that falls under the lithium-caesium-tantalum petrogenetic family. It belongs to the Spodumene subtype, and it was studied by [Oberthür in 2009](#). The Kenticha pegmatite is asymmetrically zoned from bottom to top, with a granitic lower zone, a Spodumene-free intermediate zone, and a Spodumene-bearing upper zone that is highly enriched in Li_2O (up to 3.21%). [Tadesse and Zerihun](#) characterized the Spodumene-bearing upper zone based on grain size and major minerals, accessory and rare minerals as it characterized by coarse grained major minerals are Albite-quartz-spodumene-muscovitemicrocline-pegmatite, with large Spodumene and quartz crystals and coarse-grained amazonite, apatite, amblygonite, beryl, Li-Muscovite, topaz, kunzite, cassiterite and petalite are accessory and rare minerals in Kenticha.

The vertical trend of zoning in these pegmatites is from K-feldspar rich to Na-feldspar rich. Most of the pegmatites with a large number of zones consist essentially of a basal sodic aplite with an overlying microcline-quartz-albite zone, followed by a quartz-Muscovite-albite-spodumene zone (Tadesse 2001). According to Tadesse (2001), the sequence of zoning in this Pegmatite consists of a border zone, first, second and third intermediate zones and a core zone (the last formed) and from these zones, the third intermediate zone extends upward with a major mineral assemblage are albite, spodumene, amazonite, amblygonite, microcline and sericite. The accessory and ore minerals in this zone include apatite, Li-mica, tantalite, topaz, beryl, pollucite and ixiolite.

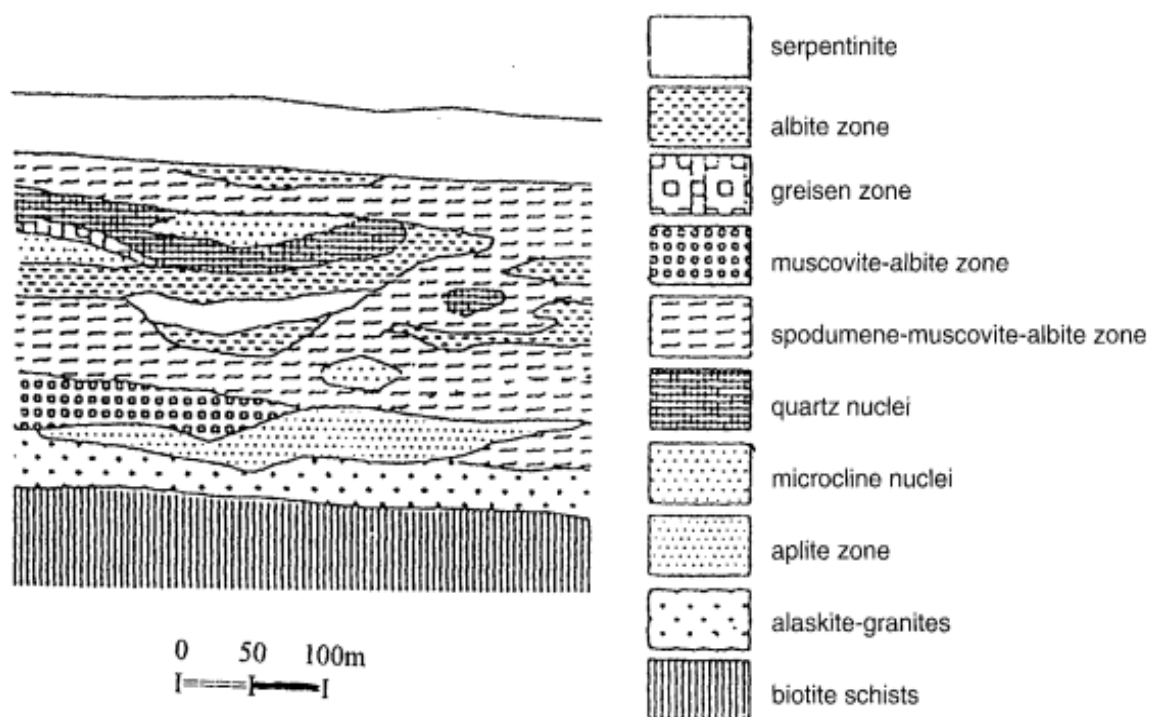


Fig.1 Schematic representation of a vertical zonation of the Main Kenticha pegmatite-granite, rare-metal mineralization (Tadesse 2001).

Recent research by Bekele and Schmerold (2020) identifies three potential sources of lithium in the Danakil Depression. Lithium is mobilized during interactions between water and rocks by hot meteoric and geothermal fluids. This happens due to the intense volcano-tectonic processes. The current hydrological conditions also suggest that surface runoff from the basement and Mesozoic sedimentary rocks exposed along the western rift margin of the

Danakil Depression can cause lithium mobilization. Moreover, the variable lithium contents in different layers of the evaporite sequence suggest that lithium originated from seawater evaporation before the Danakil Depression became a closed basin. Further research is necessary to evaluate the potential of lithium resources as a primary product or a secondary byproduct during potash mining.

Spodumene, a member of the pyroxene group, is a complex single-chain aluminum silicate (Peltosaari et al., 2015). It occurs naturally in alpha (α) form, known as α -spodumene, which has a densely packed crystal structure that is resistant to direct leaching (Karrech et al., 2020). To extract lithium effectively, early-stage processing requires extensive crushing, grinding, and milling (Comminution) of α -spodumene. A typical pegmatite deposit may contain quartz, sodium-feldspar, spodumene, lepidolite, petalite, lithiophilite, microcline, and variable amounts of muscovite (1-5%). Trace amounts of Ta-Nb phases, commonly columbite, tantalite, and other accessory phases such as spessartine, biotite, pollucite, amphibole, and other minerals (Fe-Ti oxides, tourmaline, chlorite, apatite) can also be found (Grammatikopoulos et al., 2009). The study area in Kenticha typically includes albite, microcline, Spodumene, and minor Muscovite.

2.2 Comminution (Size Reduction) Circuit for Li -Pegmatite

The initial stage in extracting minerals from host rocks involves crushing and grinding the rock to achieve a high degree of liberation, which is essential for efficient physical separation processes (Mankosa, 1989). To develop an effective concentration process for each ore, mineralogical properties such as modal mineralogy, particle size distribution, morphology, texture of particles, and degree of liberation must be considered (Hamid, 2019).

In minerals beneficiation applications, comminution circuits' primary function is to liberate valuable minerals for downstream separation processes like flotation (Little. et al., 2017). In the past, comminution circuits' design and optimization were based on achieving a target particle size distribution at an optimized throughput while considering energy efficiency and equipment wear rates (Little. et al., 2017). However, comminution remains the largest energy consumer on most mine sites, with specific energy consumption typically ranging from a few kWh/t for crushing to over 100 kWh/t for ultra-fine grinding (Wang, 2011).

To upgrade the lithium content in the finer fraction of the calcined spodumene ore, [Muhammad et al. \(2022\)](#) investigated the energy efficiency of different grinding circuits. The primary and secondary jaw crushing and tertiary cone crushing reduce the run-of-mine spodumene ore to -16 mm, which is then fed to a ball mill ([Bale and May, 1989](#)). The under size (-250 μm) fraction from the ball mill discharge is fed to cyclones to remove the slimes (-20 μm) as tailings, and the cyclone underflow is fed to the flotation circuit ([Bale and May, 1989](#)). The oversize ($+250$ μm) from the ball mill discharge is screened at 800 μm where the undersize is subjected to magnetic separation to produce a glass-grade spodumene in the non-magnetic fraction ([Tadesse,2019](#)).

The Closed-circuit grinding resulted in 89% lithium recovery of the finest size fractions (-0.6 mm) while open-circuit grinding led to 65% lithium recovery for the same grinding time and Closed-circuit grinding consumed lower energy than open-circuit grinding ([Muhammad et al., 2022](#)). According to [Muhammad et al., \(2022\)](#), the grade of the finest size fraction in the case of the open-circuit grinding was 1.7 times more than that in the case of the closed-circuit grinding.

2.3 Crushing and Grinding Controlling Parameters on Breakage Mechanism of Li- Pegmatite

Research in flotation and process mineralogy is leading to queries as to whether more should be demanded from the comminution circuit in terms of particle preparation. For example – if particle shape affects hydrophobicity, can mill operating conditions be adjusted to produce particles with shape characteristics which are more amenable to flotation ([Little et al., 2017](#)). The most common change is in the crusher's closed side setting (CSS), which enables the production of rock products in the desired size range however, Crusher parameters, such as stroke or eccentric speed, are rarely changed because changing them is time-consuming ([Bengtsson,2022](#)). The breakage of particles in grinding mills is highly dependent on design and operating parameters ([Mankosa, 1989](#)).

As per [Mankosa, \(1989\)](#), the quality of particles produced by grinding mills is determined by the breakage mechanism, which affects their size and distribution. The main mechanism is destructive impact, but other mechanisms like abrasion, primary and secondary cleavage into blocks also contribute and [Nakach et al., 2004](#)) described the role of these mechanisms are

dependent on the grinding mill's operating conditions. Factors like feed rate, air flow rate, classification tube height, nozzle angle, grinding fluid type, holdup amount, pressure, and classifier frequency also affect product fineness and particle size distribution.

2.4 Particle Size Distribution

In the field of mineral processing, it is crucial to measure the size distribution of ground materials to improve comminution efficiency. The size distribution is usually skewed, and a normal distribution only occurs for narrow size ranges. The particle size plays a critical role in the liberation and separation of minerals, and it is vital to assess the particle size distribution of the ore processed during different stages, such as crushing and grinding, to control the productivity of the overall mining operation. Mineral processing plants require the optimum size distribution and sufficient mineral liberation for product grade and mineral recovery. The particle size influences comminution properties, and different tests ranging from crushing to grinding and very fine grinding are employed accordingly (Allen, 2003; Kursun, 2009). Selecting a suitable test method requires taking into account the type of breakage mechanism in a certain crusher or mill type, as well as the stress intensity and rate (Mwanga, 2015; Taşdemir and Taşdemir, 2009). They also studied the use of particle size in developing sampling protocols for quality control and in modeling and simulating comminution unit operations. Furthermore, particle size parameters are essential inputs for plant equipment models, such as cyclones or flotation cells.

2.5. Conclusions from Literature review

The main findings from the Literature review part shows that, although several researchers have been targeting Lithium deposits from Ethiopia, they have been focusing only on mineralogy and chemical composition aspects. So that, whilst others have been investigating the processing of Kenticha deposits, columbo-tantalite and magnetite have been in the main focus. Consequently, there has not been published research works concerning the processing of Lithium-bearing ores from Kenticha, Ethiopia, what motivates carrying out the present investigation.

3. MATERIALS, ANALYSIS METHODS AND PROCEDURES

3.1. Materials

3.1.1. Sampling and samples preparation

Samples were collected from the Kenticha mine, a tantalum and lithium mine located in the Oromia Region of Southern Ethiopia. It is one of the largest tantalum reserves in the country, having estimated reserves of 116 million tonnes of ore grading 0.02% tantalum. Four kg of spodumene, 160 mm maximum in size were collected from the deposits and properly cleaned to remove soils and other contaminants, as can be seen in Figure No. 2. The rocks were then reduced in size by using a manual hammer till 10 mm maximum in size.

3.1.2 Characterization of raw materials



Fig. 2 A representative spodumene sample from Kenticha, Ethiopia

The hammered samples were then subjected to crushing and grinding operations by using Laboratory Jaw Crusher and a Laboratory Balls mill. The small rocks were then primary crushed with a single-stage laboratory jaw crusher (Retsch BB200 Mangan, 1.5 kW, Germany) at Ethiopian Geological Survey Geo science Laboratory, around Mekanisa, Addis Ababa, with close side setting (CSS) 1mm and open side setting (OSS) 10mm reduced the size from the range of 10 mm to 5-0.8mm size range. Secondary crushing was then conducted to reduce the size from 5-0.8 to 0.063 mm (63 μ m).

The crushed materials were then dry-grounded in the laboratory ball mill (Retsch RS200, 1.5 kW, Germany) at Ethiopian Geological Survey Geoscience Laboratory, around Mekanisa, Addis Ababa, until a particle size from $-500\mu\text{m} + 63\mu\text{m}$ was achieved. The operational and materials parameters of the spodumene sample under study are summarized in Table 2 and the particle size distribution after crushing is shown in Figure 4.

Table 2. Operational ball mill and material parameters of the spodumene sample under study.

Mill type	Items	Parameters	Value
Ball mill	Mill	Inner diameter D, mm	100
		Length L, mm	200
		Volume V, cm^3	80
	Ball	Material	Stainless steel
		Average ball weights, g	32.24
		Diameter, mm	25
		Number of balls	10
		Total mass, kg	322.4
	Speed	Critical speed N_c , rpm	529
		Operational speed (75% of critical speed), rpm	400
	Material	Type	Spodumene
		Feed amount (g)	Vary
		Feed size μm	500-63

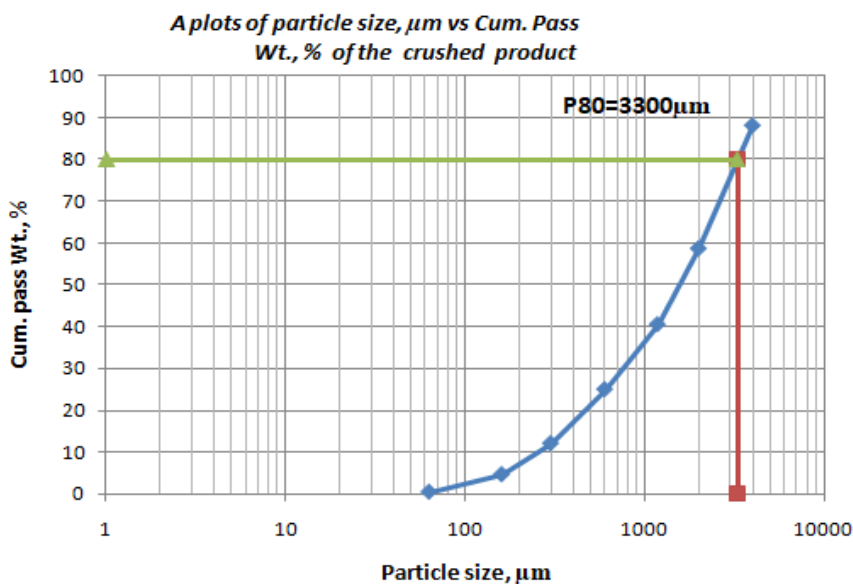


Fig.4 Particle size distribution crushed product

Four grinding tests were conducted, with each test using identical samples that were mixed thoroughly through coning and quartering to ensure representativeness. The ball mill was operated with different grinding conditions, in accordance with Table 2. The grinding tests were conducted under dry conditions, with each sample being ground for one minute using the ball mill. Four identical samples were milled under different operating parameters, with the feed amount and rotational speed being varied at four levels. The rotational speed levels were 350 rpm, 400 rpm, 450 rpm, and 500 rpm, while the grinding period was kept constant at one minute.

S1: Operational speed 350 rpm, Feed amount 400g, feed size 500-63 μ m;

S2: Operational speed 400 rpm, Feed amount 350g, feed size 500-63 μ m;

S3: Operational speed 450 rpm, Feed amount 300g, feed size 500-63 μ m;

S4: Operational speed 500 rpm, Feed amount 250g, feed size 500-63 μ m;

The particle size distribution of the ball mill products was then analyzed and compared for each of the four grinding tests. This information would help to determine the optimal operating parameters for the ball mill in the subsequent stages of the project.

3.1.3. Test procedures

Fresh and representative spodumene ore sample from Kenticha area were subjected to mineralogical and chemical analyses through X-ray diffraction (XRD) and atomic absorption (AAS). The feed material for comminution tests was a spodumene, lithium ore, with other gangue mineral types: spodumene (49.1 %), albite (24.1%), Quartz (13.8 %), Iron oxides (1%), Mica (7 %) and microcline (5 %), XRD results are shown in Fig.3.

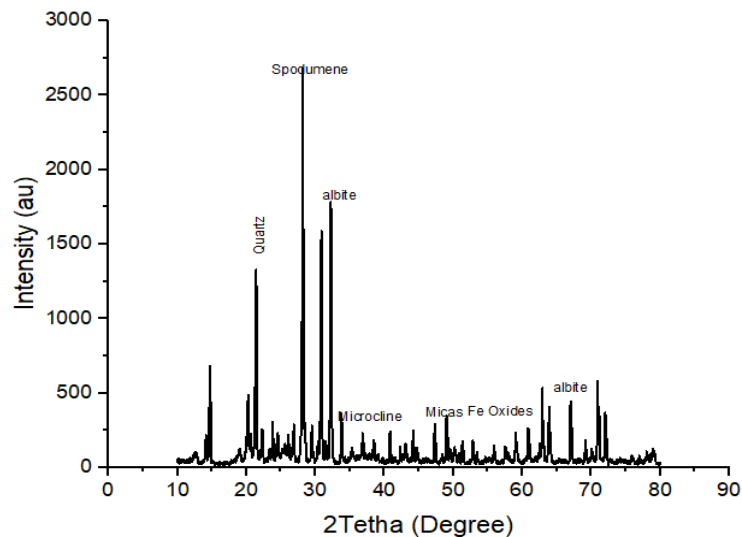


Fig 4. Mineralogical composition of the spodumene sample using XRD technique
 AAS studies show that representative sample of has 2.23 % Li_2O . Other compositions are 53.24% SiO_2 , 28.74% Al_2O_3 , 1.24 % Fe_3O_4 , 3.6% MgO , 3.36% Na_2O , and 0.16% K_2O , 0.14 P_2O_5 with loss of ignition 5.38 as shown in table 3.

Table 3. The chemical composition of the sample under study

Chemical contents in oxide form	SiO_2	Al_2O_3	Fe_3O_4	MgO	Na_2O	K_2O	P_2O_5
Content (%)	53.24	28.74	1.24	3.6	3.36	0.16	0.14

3.3.3 Grinding Tests

The grinding tests were carried out in dry conditions. Ball milling tests were performed using a laboratory-scale ball mill (**FRITSCH Planetary Ball Mills**) Geoscience laboratory, Geological Institute of Ethiopia. The diameter and the length of the drum for the ball mill were 10 and 25 cm, respectively. A stainless-steel cylinder was used as the drum in the ball milling tests, in which 322.4 g of stainless-steel balls with diameters of 2 cm were used. The critical rotational speed for centrifuging in ball and rod milling can be calculated as follows ([Abouzeid and Fuerstenau, 2012](#)):

$$N_c = \frac{30}{\pi} \sqrt{\frac{2g}{D-d_r}}$$

$$\begin{aligned}
 &= N_c = 30/\pi[\sqrt{(2g)} / \sqrt{(D-r)}] && \text{where:} \\
 &= (9.55*\sqrt{2g})/\sqrt{D-r} && N_c = \text{critical speed (in rpm)} \\
 &= 9.55*4.42/ \sqrt{(D-r)} && D = \text{diameter of the mill (in meters)} \\
 &= 42.3/\sqrt{(D-r)} && r = \text{diameter of the balls (in meters)} \\
 &= 42.3/\sqrt{(0.10-0.025)} && g= \text{gravitational acceleration 9.8m/s} \\
 &= 42.3/0.075 \\
 &= \mathbf{564 \text{ rpm}}
 \end{aligned}$$

The critical speed calculated for the laboratory-scale ball mill used in the grinding tests was **564 rpm**. This value indicates the rotational speed at which centrifugal forces equal the gravitational forces on the grinding balls in the drum, resulting in effective grinding and particle size reduction. It is important to operate the ball mill at or near (above 75%) the critical speed to ensure optimal grinding performance. If the ball mill operate at 80% N_c , the operational speed could be around 451.2 rpm is optimum.

The stainless steel balls in the ball milling tests used, as they are durable and resistant to wear and corrosion. In addition, the size and amount of grinding media used can also affect the comminution behavior and should be carefully selected based on the specific application.



Fig. 5 The ball, ball mill and milled products of the sample

3.4. Particle Size Analysis

3.4.1 Particle Size, Distribution Analysis

The sample was sieved using a set of 4000, 2000, 1180, 600, 300,160 and 63 μm sieves the laboratory sieves (for the chemical analysis and physical properties of minerals.Fig.7 shows the particle size distribution of the jaw crusher product of sample.



Fig.6. Standard test sieves

*Table 4.*The product of crusher of samples

Particle size, μm	Weight, g	Weight Retained (%)	Cum.Weight Pass (%)	Cum.Weight Retained (%)
4000	46.63	11.66	88.34	11.66
2000	118.23	29.56	58.77	41.22
1180	72.83	18.21	40.56	59.43
600	62.37	15.59	24.97	75.02
300	51.92	12.98	11.98	88.01
160	29.81	7.45	4.53	95.46
63	16.87	4.22	0.31	99.68
-63	1.25	0.31	0	100

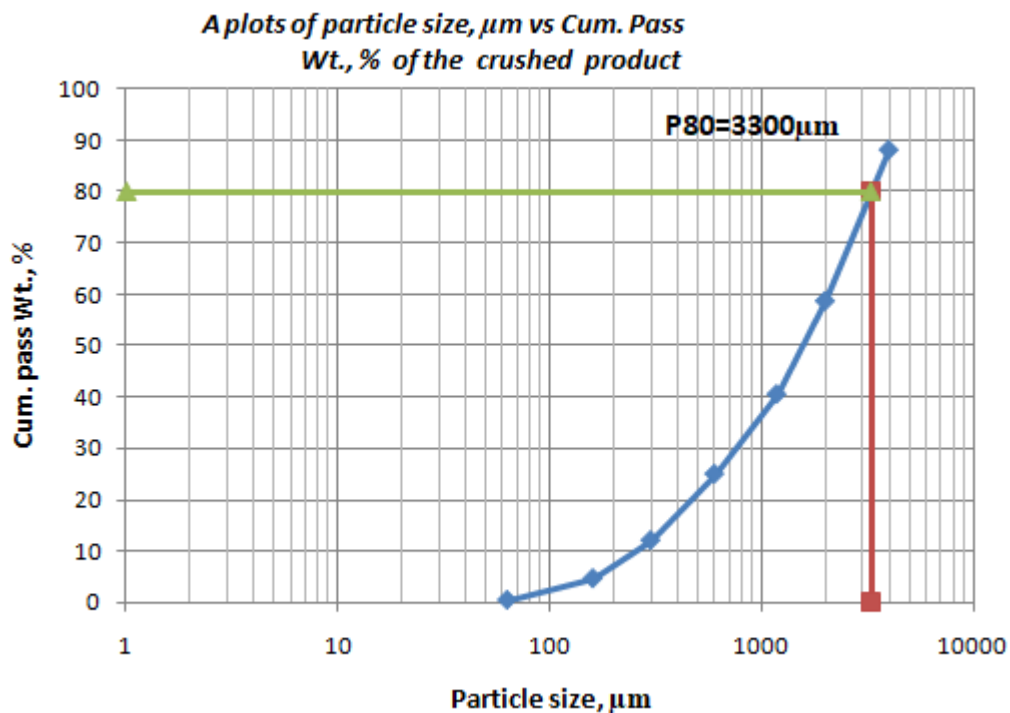


Fig.7: Particle size distribution of the jaw crusher product of sample

Then the 80 % particle's size is $P80=3300\mu\text{m}= 3.3\text{mm}$

Mass feed rate (tonnage) can be calculated by dividing the total feed mass with total time required for crushing. Tonnage = 1kg of spodumene feed / crushed for 1 minutes = 1kg/ min. = **0.06 t /h = 60kg /h**

Table 5 Particle size distribution after ball milling for sample one (S_1)

Particle size, μm	Weight, g	Weight Retained (%)	Cum.Wt. Pass (%)	Cum.Wt. Retained (%)
2000	51.05	12.69	87.3092	12.69
1180	44.80	11.13	76.17	23.48
600	94.50	23.48	52.68	47.31
300	107.99	26.84	25.84	74.15
160	80.41	19.98	5.83	94.14
63	22.74	5.65	0.20	99.79
-63	0.80	0.20	0	100

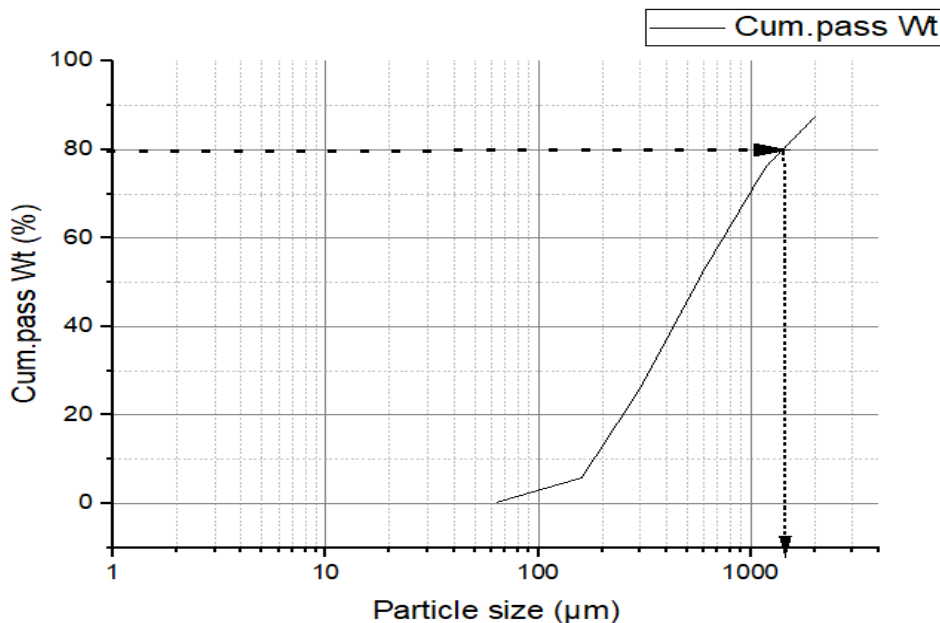


Fig. 8. Shows the particle size distribution of sample one (S1) after ball milling. Particle size is measured in micrometers (μm), and the weight of each particle size fraction is recorded along with the corresponding weight retained and cumulative weight passes and retained percentages.

Then the 80 % particle's size is $P_{80} = 1400\mu\text{m} = 1.4\text{mm}$

The largest particle size measured was $2000\mu\text{m}$, with a weight of 51.05g and weight retained percentage of 12.69% . The smallest particle size measured was less than $63\mu\text{m}$, with a weight of 0.80g and weight retained percentage of 0.20% . The particle size distribution is relatively wide, with a broad range of particle sizes present in the sample.

Condition 1 for S1

The feed to the ball mill circuit is 80% is 3300 (F80) microns, 80% pass (P80) of the ball mill product 1400 microns and the bond work index of the ore is 11.4 kWh/t , calculate the mill power required for the circuit in kW.

To calculate mill power, using the following formula, the Bond work index most commonly used formula,:

$$F_{80} = 3300\mu\text{m}$$

The work index W_i spodumene (Bond) is 11.4 kWh/t

The calculations for the mill power required for the circuit are specific energy consumption (W):

$$\begin{aligned}
 W &= W_i [10/\sqrt{P80} - 10/\sqrt{F80}] = 11.4 [10/\sqrt{1400} - 10/\sqrt{3300}] \\
 &= 114*(0.027-0.017) \\
 &= 1.14 \text{ kWh/t}
 \end{aligned}$$

Using the value, the power required for the circuit can be calculated as follows:

$$\begin{aligned}
 \text{Power} &= W * \text{tonnage thus tonnage} = 0.0004\text{t/minute} = 0.024\text{t/h} \\
 &= 1.14 \text{ kWh/t} * 0.024\text{t/h} \\
 &= 0.027\text{kW} = 27\text{W}
 \end{aligned}$$

Therefore, the mill power required for grind 400g of sample was 27W

Table.6 Particle size distribution after ball milling for sample two (S₂)

Particle size, μm	Weight, g	Weight Retained (%)	Cum.Wt. Pass (%)	Cum.Wt. Retained (%)
2000	22.6768	6.4921	93.5079	6.4921
1180	58.35	16.71	76.79	23.20
600	86.95	24.89	51.89	48.10
300	87.36	25.01	26.88	73.11
160	66.07	18.91	7.97	92.02
63	26.31	7.53	0.43	99.56
-63	1.52	0.43	0	100

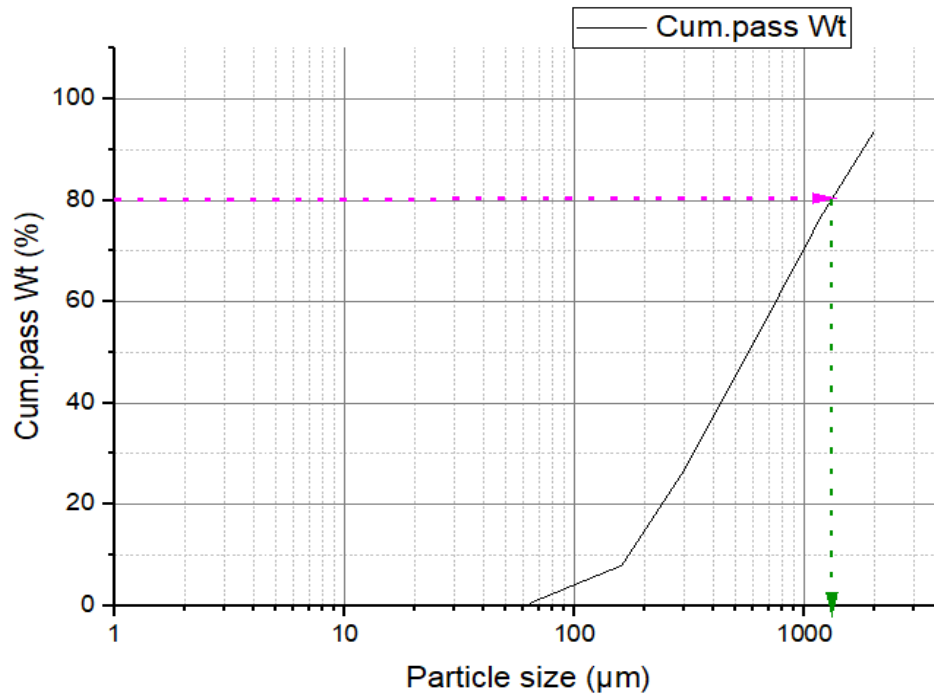


Fig. 9 Shows the particle size distribution of sample one (S2) after ball milling. Particle size is measured in micrometers (μm), and the weight of each particle size fraction is recorded along with the corresponding weight retained and cumulative weight passes and retained percentages.

Then the 80 % particle's size is $P_{80}=1300\mu\text{m}=1.3\text{mm}$

The particle size distribution is relatively wide, with a broad range of particle sizes present in the sample and $P_{80}=1300\mu\text{m}=1.3\text{mm}$

Condition 2 for S2

The feed to the ball mill circuit is 80% is 3300 (F80) microns, 80% pass (P_{80}) of the ball mill product 1300 microns and the bond work index of the ore is **11.4** kWh/t, calculate the mill power required for the circuit in kW.

To calculate mill power, use the following formula: $F_{80} = 3300\mu\text{m}$

The work index W_i spodumene is 11.4kWh/t

The calculations for the mill power required for the circuit are specific energy consumption (W):

$$\begin{aligned} W &= W_i [10/\sqrt{P_{80}} - 10/\sqrt{F_{80}}] = 11.4 [10/\sqrt{1300} - 10/\sqrt{3300}] \\ &= 114*(0.028-0.017) \\ &= 1.254\text{kWh/t} \end{aligned}$$

Using the value, the power required for the circuit can be calculated as follows:

Power = W * tonnage thus tonnage = 0.00035t/minute =0.021t/h
 = 1.254Wh/t * 0.021t/h
 = 0.026kW =26W

Therefore, the mill power required for grind 400g of sample was 26W

Table 7 Particle size distribution after ball milling for sample three (S₃)

Particle size, μm	Weight, g	Weight Retained (%)	Cum.Wt. Pass (%)	Cum.Wt. Retained (%)
2000	18.81	6.27	93.72	6.27
1180	46.34	15.45	78.27	21.726
600	77.74	26.27	51.99	48.00
300	64.69	21.57	30.42	69.57
160	60.76	20.26	10.15	89.84
63	29.64	9.88	0.27	99.72
-63	1.88	0.27	0	100

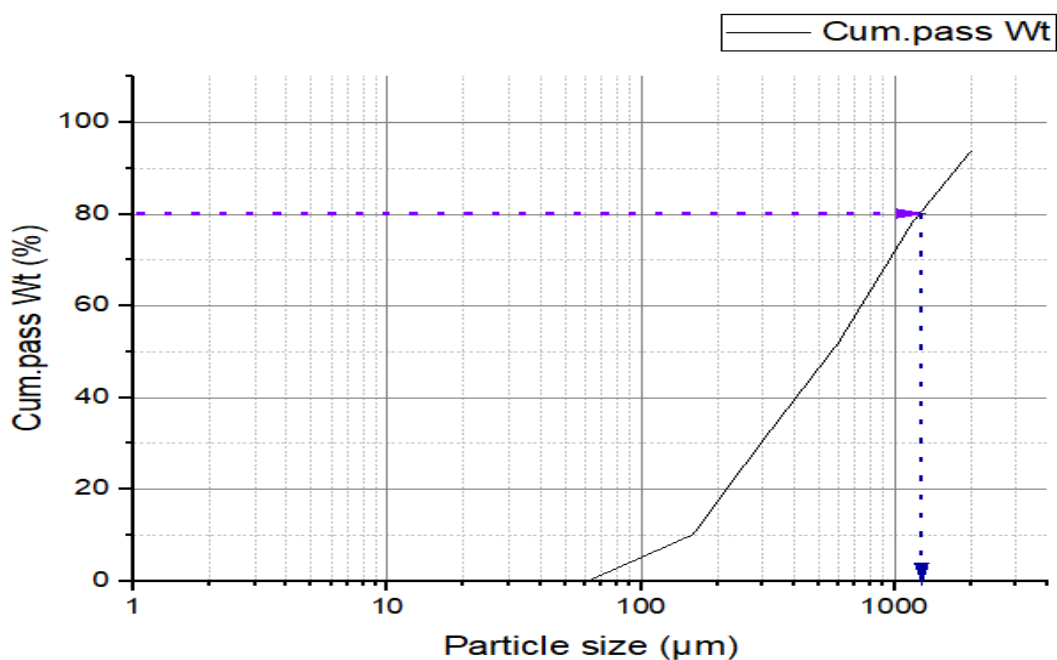


Fig. 10 Shows the particle size distribution of sample one (S₃) after ball milling. Particle size is measured in micrometers (μm), and the weight of each particle size fraction is recorded along with the corresponding weight retained and cumulative weight passes and retained percentages

Then the 80 % particle's size is $P_{80}=1200\mu\text{m}=1.2\text{mm}$

The cumulative weight pass increases as the particle size decreases, with the largest cumulative weight pass at $-63\mu\text{m}$ (100%). The cumulative weight retained decreases as the particle size decreases, with the largest cumulative weight retained at $2000\mu\text{m}$ (6.27%). Overall, the particle size distribution shows that the ball milling process resulted in a range of particle sizes, with a significant number of particles in the $600\mu\text{m}$ size range.

Condition 3 for S3

The feed to the ball mill circuit is 80% is 3300 (F80) microns, 80% pass (P_{80}) of the ball mill product 1200 microns and the bond work index of the ore is 11.4 kWh/t, calculate the mill power required for the circuit in kW.

To calculate mill power, use the following formula: $F_{80} = 3300\mu\text{m}$

The work index W_i spodumene is 11.4kWh/t

The calculations for the mill power required for the circuit are specific energy consumption (W):

$$\begin{aligned} W &= W_i [10/\sqrt{P_{80}} - 10/\sqrt{F_{80}}] = 11.4 [10/\sqrt{1200} - 10/\sqrt{3300}] \\ &= 11.4*(0.029-0.017) \\ &= 1.368\text{kWh/t} \end{aligned}$$

Using the value, the power required for the circuit can be calculated as follows:

$$\begin{aligned} \text{Power} &= W * \text{tonnage} \quad \text{thus tonnage} = 0.00030\text{t/minute} = 0.018\text{t/h} \\ &= 1.368\text{kWh/t} * 0.018\text{t/h} = 0.0246\text{kW} = 24.6\text{W} \end{aligned}$$

Therefore, the mill power required for grind 400g of sample was 24.6W

Table 8 Particle size distribution after ball milling for sample four (S₄)

Particle size, μm	Weight, g	Weight Retained (%)	Cum.Wt. Pass (%)	Cum.Wt. Retained (%)
2000	0.5	0.20	99.79	0.20
1180	3.37	1.35	98.44	1.55
600	42.06	16.88	81.56	18.43
300	79.32	31.97	49.59	50.40
160	83.80	33.63	15.96	84.03
63	37.70	15.12	0.83	99.16
-63	2.07	0.83	0	100

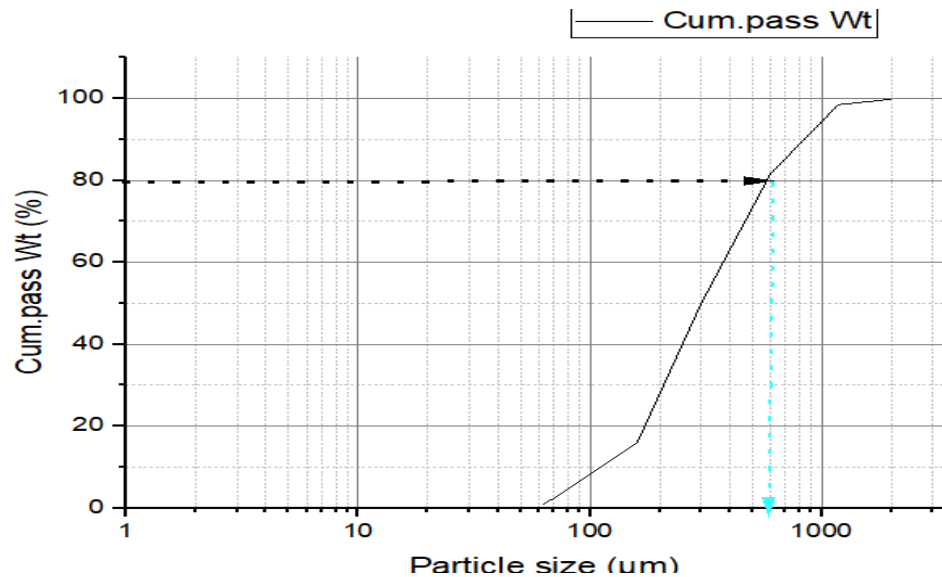


Fig.11 shows the particle size distribution for sample four (S4) after ball milling.

$$P80=600\mu\text{m}= 0.6\text{m}$$

Fig.11 show that the majority of the sample's weight falls within the 300-600 μm range, with 31.97% of the sample weight retained within this range. The distribution of the sample's weight decreases sharply in smaller size ranges, with only 0.83% of the sample weight being retained in the smallest size range (-63 μm).

The feed to the ball mill circuit is 80% is 3300 (F80) microns, 80% pass (P80) of the ball mill product **1200** microns and the bond work index of the ore is 11.4 kWh/t, calculate the mill power required for the circuit in kW.

To calculate mill power, use the following formula: $F80 = 3300\mu\text{m}$

The work index **Wi** of spodumene is 11.4kWh/t

The calculations for the mill power required for the circuit are specific energy consumption

(W):

$$W = Wi [10/\sqrt{P80} - 10/\sqrt{F80}] = 11.4 [10/\sqrt{600} - 10/\sqrt{3300}]$$

$$= 114*(0.041-0.017)$$

$$\underline{=2.736 \text{ kWh/t}}$$

Using the value, the power required for the circuit can be calculated as follows:

$$\text{Power} = W * \text{tonnage} \quad \text{thus tonnage} = 0.00025\text{t/minute} = 0.015\text{t/h}$$

$$= 2.736\text{kWh/t} * 0.015\text{t/h}$$

$$\underline{= 0.041\text{kw} = 41\text{W}}$$

Therefore, the mill power required for grind 400g of sample was 41W

3.4.2 Mineral Content Analysis by X-ray Diffraction (XRD) Technique

After 10 minutes of sieving, the milling product was divided into six fractions, with only those between -300+63 μm being selected for further analysis. Mineralogical analysis was carried out using X-ray diffraction (XRD) technique for each of the selected fractions. The samples were packed into a holder and scanned under controlled conditions.

Specialized software (Match3 and origin) were utilized to analyze the resulting diffraction data, enabling the identification of minerals present and measurement of their relative abundances. This analysis provided crucial insights into the mineralogy of the milling product, including any changes that may have occurred during the milling process.

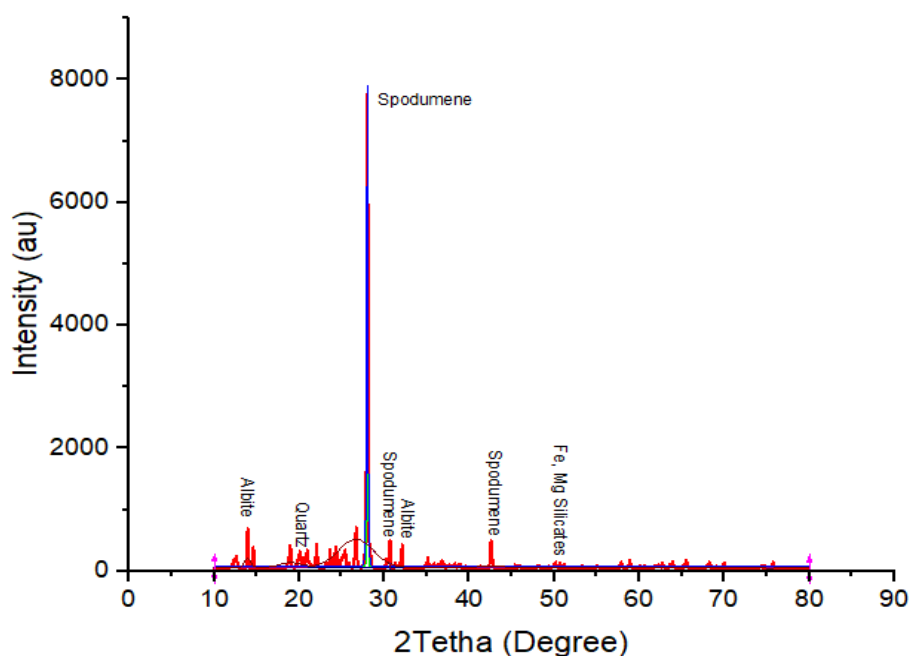


Fig.12 Mineralogical analysis of spodumene by the XRD technique for sample one (S_1)

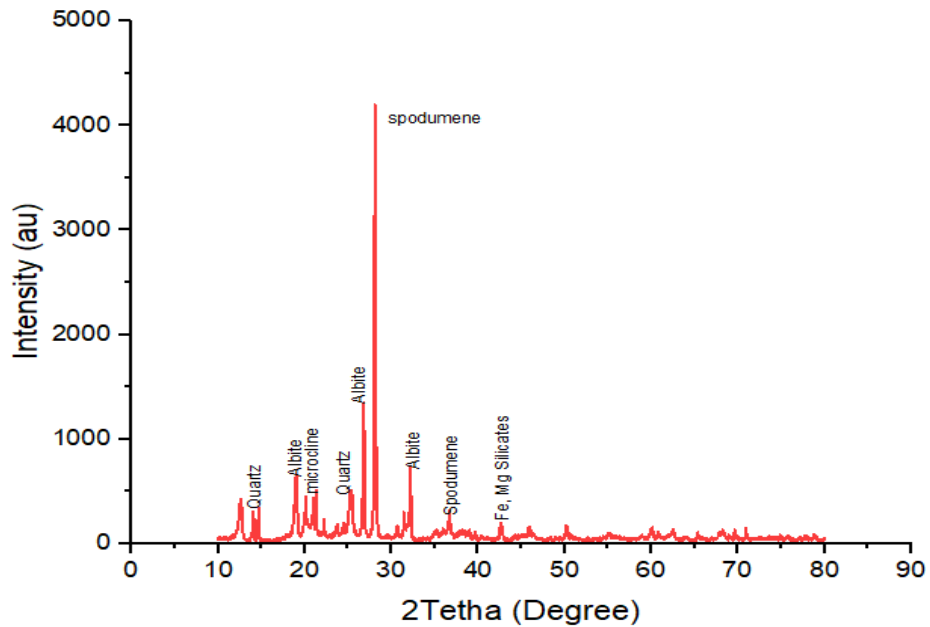


Fig.13 Mineralogical analysis of spodumene by the XRD technique for sample one (S2)

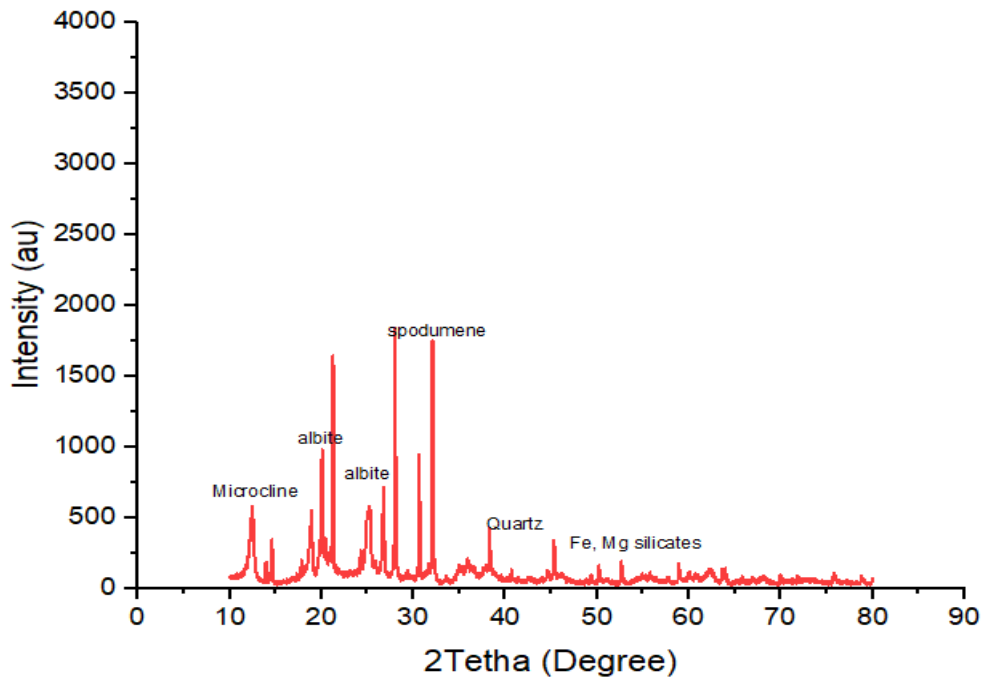


Fig.14 Mineralogical analysis of spodumene by the XRD technique for sample one (S3)

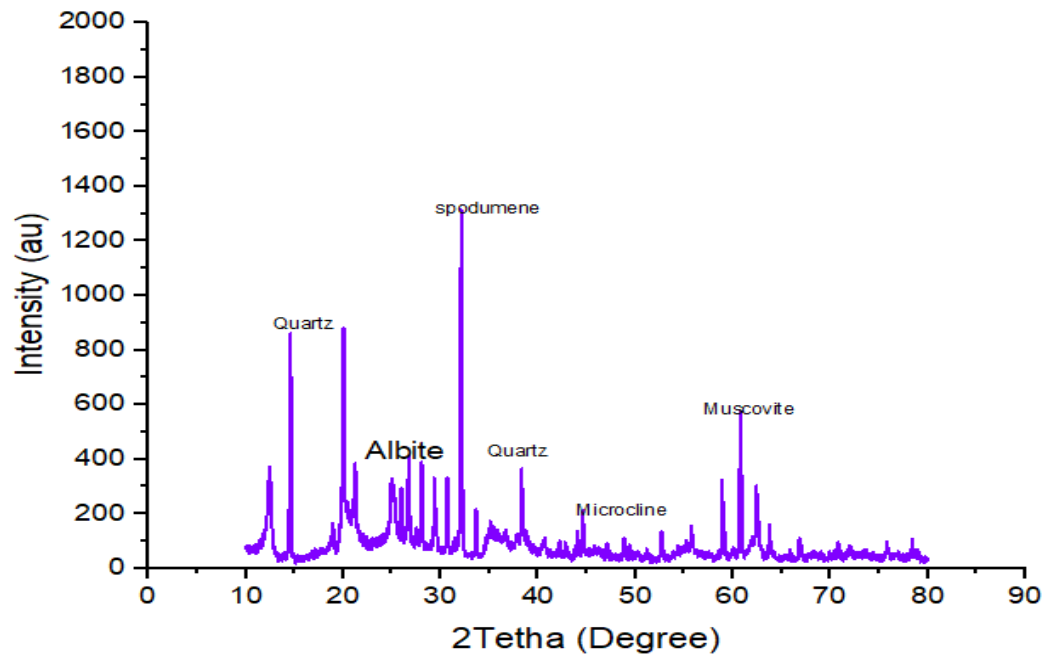


Fig.15 Mineralogical analysis of spodumene by the XRD technique for sample one (S_4)

4. DISCUSSION AND INTERPRETATION OF TEST RESULTS

4.1 Operation of Comminution Systems (Grinding Parameters).

The mineral processing industry has conducted numerous investigations to optimize the comminution process, including the characterization of mineral and geochemical properties such as content, size, texture, and fracture, as well as the design and operation of comminution systems. Size reduction, which is a power-intensive stage of mineral processing, has been the focus of much research aimed at achieving the most optimal design of crushing and grinding circuits, as well as pre-treatment technologies, such as calcination of spodumene prior to crushing. Comminution can be achieved through crushers and mills, the latter of which involves crushing and grinding. However, it can be challenging to limit the production of over- and under-sized particles during the reduction process, leading to an over-representation of fines. The comminution behavior, which is the interaction of material properties and process parameters, can alter the size, chemical composition, and surface area of materials. In the case of this work, comminution of spodumene is essential for separating lithium-bearing minerals from the host rock, two dominant parameters (amount of feed and rotational speed of the mill) were selected to investigate their effect during grinding.

4.1.1 Optimizing Breakage Mechanism Using Critical Speed

Using mill and ball diameters, the critical speed calculated for the laboratory-scale ball mill used in the grinding tests was 564 rpm. This value indicates the rotational speed at which centrifugal forces equal the gravitational forces on the grinding balls in the drum, resulting in effective grinding and particle size reduction. It is important to operate the ball mill at or near (above 75%) the critical speed to ensure optimal grinding performance. If the ball mill operates at 80% N_c , the operational speed could be around 451.2 rpm optimal grinding performance.

A ball mill operating at 60% of the critical speed abrasion and attrition are dominant and a ball mill operating at 80% of the critical speed, predominantly impact breakage mechanism. According to this calculation sample three (3) and four (4) were ground by impact breakage as the operational speed was above 451.2 rpm or a ball mill operated above 80% of the critical speed.

4.2 Characterization of Mineral and Geochemical Properties

Mineralogical analysis using X-ray diffraction revealed that the lithium bearing pegmatite from kentcha area (run of mine sample) consists mostly of spodumene, with significant amounts of feldspar, quartz and micas. XRD tests results (Figs. 3) showed a spodumene, lithium ore, (49.1 %), with other gangue mineral types: albite (24.1%), Quartz (13.8 %), Iron oxides (1%), mica (7 %) and microcline (5 %). The AAS studies (Table 3) indicate that the spodumene ore sample contains 2.23% Li₂O which is a significant amount.

The other mineral compositions also provide valuable information about the composition of the ore sample, including the high percentages of SiO₂ and Al₂O₃, which are common gangue minerals. The presence of significant amounts of MgO and Na₂O may also impact the processing and extraction of lithium from the ore. The P₂O₅ content is relatively low, and the loose of ignition (LOI) of 5.38% indicates that there may be some organic matter present in the sample that could impact processing. Overall, these results will be useful in determining the potential economic viability of extracting lithium from this spodumene ore sample.

4.2.1 Effect of Grinding on Mineral Content

When grinding product of all four samples analyzed by XRD technique, the mineral content as shown in Fig. 12- 15 (below 75µm size), the spodumene content decreased as particle sizedecreased from sample one (S1) to sample four (S4).

The XRD analysis results are listed in the following table (Table 9)

Sample No	Mineral contents, % analyzed by XRD							80% pass size (P80) µm
	Spd	Albt	Qtz	Mcln	Mst	Bt	Fe,Mg silicates	
S1	58.9	34.1	3	2	1		1	1400
S2	50.5	25.2	10.3	2	3		5	1300
S3	49.7	25.4	10.3	6.3	3		6.4	1200
S4	41.1	13.4	20.8	5.6	14.1	1	3	600

Grinding pegmatitic ore to produce the concentrate liberates spodumene from the gangue minerals induces amorphicity in the mineral by destroying the crystallinity at particle surfaces (Gasalla et al., 1987; Vieceli et al., 2017). The fine grinding process used in this study to investigate the impact of breakage mechanism on the grinding product, as feed amount decrease and the rotational speed of the mill increase, the reduction in the size of the grains also increased and as reduction became higher, it decreases in the degree of crystalline, which is reflected in the broadening and shortening of peaks in XRD analysis, the differences as shown Fig. 12- 15. Generally, (Gasalla et al., 1987) explained amorphous materials display increased reactivity and less resistance to reagent attack showing improved recoveries during leaching. Over all, the broadening and shortening of peaks in XRD analysis (Fig. 12- 15) were amorphicity in the mineral by destroying the crystallinity of spodumene and this led the spodumene to be lower in content (Table 9).

Another cause spodumene to be reduced during comminution parameters changes could be association effects. Some mineral such as quartz harder than spodumene with a Mohs hardness of 7, makes it resistant to abrasion and requiring more energy to break them down. Due to this, during comminution, the relatively harder minerals might be retained in coarser size fractions while softer minerals including spodumene are easily ground to finer sizes, resulting in the spodumene content was higher at lower energy grinding. However, as energy increase (rotational speed increase) the particle size decreases, the association effects become less significant and spodumene can be more easily separated from other minerals.

4.3 Assessment of Particles Size distribution

From the particle size distribution graph, the ball mill products obtained from the four grinding tests with different operating parameters for the four samples (S1, S2, S3, and S4) with varying feed amounts and rotational speed indicates that as the operational speed increases and as the feed amount decreases, the particle size distribution becomes narrower, indicating that more fine particles are being produced. Fig.16 shows the particle size distribution differences in different operational grinding conditions. With increasing rotational speed of the mill and decreasing the amount of feed to mill the cumulative pass percent was increased and 80% passing size decreased from sample one(S₁) through sample four (S₄).

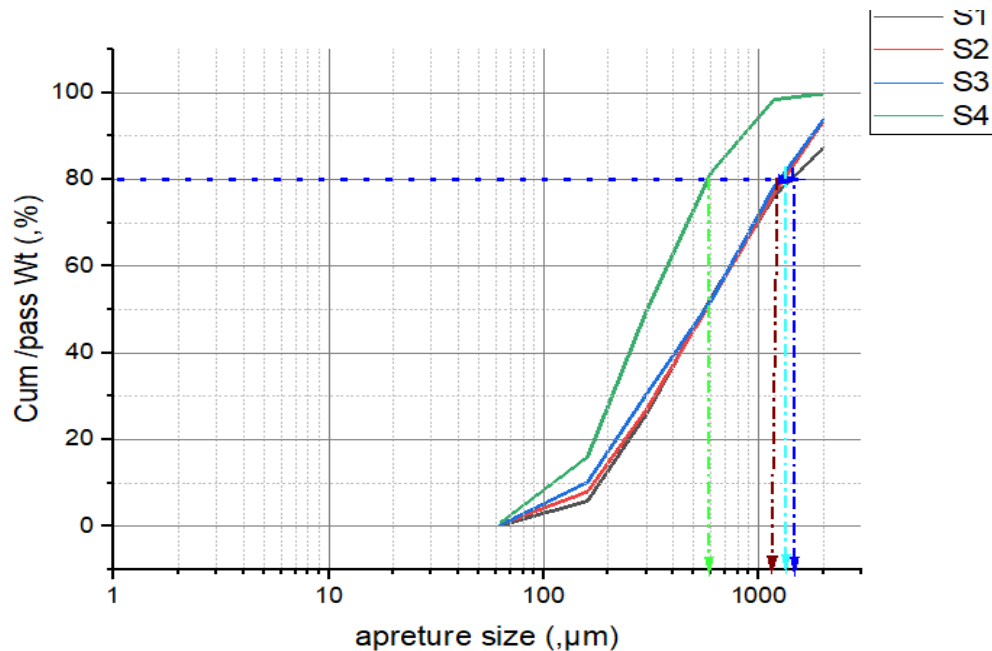


Fig.16 shows the particle size distribution differences in different operational grinding conditions.

4.4 Calculating Power Consumption

80% passing size calculated from particle size distribution graph is affected by the operational conditions, feed amount and rotational speed of the grinding mill. As the feed amount decrease and rotational speed of the grinding mill increase the 80% passing size (P80) decrease.

Table 10 the relation between P80 and power

Sample No	80% passing size, μm	Power kW
S1	1400	27
S2	1300	26
S3	1200	24.6
S4	600	41

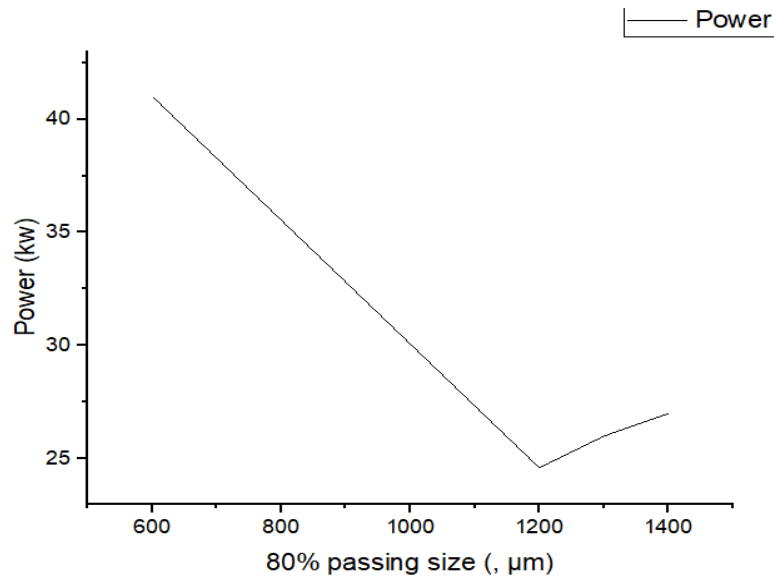


Fig. 17 relationship between the 80% passing size and the power

Fig. 17 shows that there is an inverse relationship between the 80% passing size and the power output of the grinding mill. As the power output increases (from S1 to S4), the 80% passing size decreases (from 1400 μm in S1 to 600 μm in S4). This suggests that increasing the power output of the mill can result in finer particle sizes being produced. However, it's important to note that other factors such as feed amount and rotational speed likely also played a role in determining the 80%. The power consumption of a grinding mill is directly proportional to the amount of feed processed and the size distribution of the ground product, represented by the P80 value.

A decrease in feed amount can lead to higher specific power consumption due to inefficient use of the energy provided, while increasing the rotational speed of the mill can also lead to higher power consumption as more energy is required to grind particles to a finer size. As the particle size decreases, the specific surface area of the particles increases, resulting in higher energy demands to further reduce the particle size. Therefore, achieving a very fine particle size distribution often requires higher power consumption. However, it is important to balance the energy input with the desired particle size and the associated costs of energy consumption. A more efficient comminution process that uses less energy to achieve the desired particle size may be more.

4.5 Identifying the Breakage mechanism of ball mill during the comminution process

According to the results shown in this research work, samples 3 and 4 were grounded by impact breaking mechanism as the operational speed was above 451.2 rpm or a ball mill operated above 80 % of critical speed. On the other hand, samples 1 and 2 were grounded by attrition (friction) mechanism as the operational speed was below 400 rpm or a ball mill operated below 60 % of critical speed.

These results are consistent with other author's results in the sense of the possibility for the occurrence of various breakage mechanisms within a comminution process (Varinot et. Al, 1997), but, however, one or two breakage mechanisms can have a dominant effect (Athayde and Bagatini, 2019). In this case, impact breaking mechanism and attrition (friction) mechanism are the dominant in this laboratory runs, according to the rotational speeds and the amount of feed used.

This way, the general objective, related to the investigation of the breakage mechanism of ball mill during the comminution processing of Lithium minerals from the Kenticha mine, Ethiopia, is considered as fulfilled, as well as the study of the influence on the particle size distribution and power consumption of the mill by varying the feed amount and rotational speed of the mill. The experimental analysis determined that the most effective grinding conditions were found with a milling power of 41 W, a feed amount of 250 g, and a milling speed of 500 rpm. These conditions resulted in a narrow size distribution and the desired particle size for a high spodumene concentration.

However, when the feed amount fall below 250 g or the rotational speed exceeded 500 rpm for this specific mill, it led to an increase in specific power consumption due to the inefficient use of energy, resulting in ball wearing and unnecessary use of power compared to the amount of product produced. While achieving a fine particle size distribution may require higher power consumption, it is important to balance the energy input with the desired particle size distribution and the associated costs of energy consumption.

5. CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

1. According to the Laboratory runs conditions (the rotational speeds and the amount of feed used), impact breaking mechanism and attrition (friction) are the dominant mechanisms revealed during grinding processes of Lithium minerals from the Kenticha mine, Ethiopia.
2. The optimum parameters for effective impact breaking and attrition (friction) mechanisms to produce narrow size distribution and the desired particle size for high spodumene concentration are identified as milling power: 41 W, amount of feed: 250 g and the milling speed: 500 rpm.
3. Mineralogical and chemical composition of the sample were studied by X – ray diffraction (XRD) and atomic absorption spectroscopy (AAS) showed feasible content of Li- in the spodumene . The XRD analysis identified the presence of spodumene as the main mineral, along with other minerals such as feldspar and quartz. AAS analysis showed that the sample contained a feasible amount of lithium, indicating that it could potentially be extracted and used in the production of lithium-based products.
4. The study found that reducing the feed amount and increasing the rotational speed of the grinding mill resulted in the production of very fine particles. However, this also led to an increase in power consumption. In order to calculate the power consumption, the 80% passing size (P80) was used. By using this parameter and the feed amount, the power consumption required to achieve the desired particle size distribution were calculated.
5. Therefore, while decreasing the feed amount and increasing the rotational speed may result in finer particles, it also requires higher power consumption. Finding the right balance between particle size, feed amount, and rotational speed is a key to optimizing the comminution process and reducing energy costs.

5.2 Recommendations

1. The operational and material parameters of comminution equipment may need to be adjusted to achieve the desired particle size and distribution. To optimize spodumene

comminution, researchers need to conduct extensive laboratory studies and pilot-scale tests to determine the most effective comminution techniques for specific deposits. Collaborative efforts between researchers, industry professionals, and mineral processing companies can help accelerate the development of optimal comminution strategies for extracting lithium from pegmatite.

2. It is also recommended that mineral processing plants invest in modern comminution equipment and process control technologies to optimize comminution and improve product outcomes.
3. Additionally, process control tools, such as advanced sensor and instrumentation technologies, can provide real-time measurements that enable operators to monitor and adjust comminution performance to ensure high-quality end products.

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