

Beneficiation of Lithium from Spodumene Rich Pegmatite: A Review

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ABSTRACT— Lithium, a vital metal for modern technology, has become a highly sought-after commodity in Nigeria. The country is endowed with significant lithium deposits, particularly in Kaduna, Kwara, and Niger states. These deposits have the potential to support Nigeria's economic growth and meet the increasing global demand for lithium-ion batteries, which are crucial for electric vehicles and renewable energy systems. In Nigeria, lithium-bearing minerals such as spodumene, petalite, and micas have been identified in pegmatites and granites. The deposits in Kaduna, Kwara, and Niger states are particularly promising, with spodumene being the most abundant and economically viable mineral due to its high lithium content (approximately 8 wt% Li_2O). The beneficiation of these hard rock lithium deposits in Nigeria is crucial to unlock their economic potential. This paper reviews the current state of lithium beneficiation in Nigeria, including the use of flotation, dense media separation, magnetic separation, and roasting techniques to process spodumene-bearing ores. By leveraging these technologies, Nigeria can position itself as a significant player in the global lithium market, supporting the growth of the electric vehicle industry and renewable energy sector.

Keyword: Beneficiation, Flotation, Dense Media Separation, Magnetic Separation, Roasting.

I. INTRODUCTION

Lithium, a soft and versatile metal, is in high demand globally, with a significant portion used in lithium-ion batteries, ceramics, glass, and other industries (Jaskula, 2014). Nigeria has potential lithium deposits and rock pegmatite deposits (Goonan, 2012). The country can benefit from the growing demand for lithium, driven by the increasing adoption of electric vehicles (Ober, 1994).

In the past, the United States and Chile were the largest producers of lithium, with most production coming from brine operations (Ober, 1994).

Homewever, in recent years, Chile has become the leading producer of lithium carbonate from brines, while Australia has maintained its position as the largest producer of lithium mineral concentrate (Jaskula, 2014).

Nigeria can learn from these countries and develop its lithium industry to meet the growing global demand. The country has the potential to produce lithium from its brine lakes and hard rock pegmatite deposits, which can be processed into various product types, including mineral concentrate (Goonan, 2012).

By developing its lithium industry, Nigeria can create jobs, generate revenue, and contribute to the global supply chain of this critical metal. Additionally, Nigeria can benefit from the predicted major shifts in demand for lithium, driven by the success and widespread use of electric vehicles (Ober, 1994).

With the right investment and support, Nigeria can become a significant player in the global lithium market, contributing to the country's economic growth and development (Jaskula, 2014).

Nigeria's lithium mining industry has experienced a revival in recent years, driven by the growing demand for electric vehicles and the resulting surge in lithium prices (MMSD, 2022). After a hiatus of several decades, artisanal miners and large capitalization miners are once again showing keen interest in lithium mining in Nigeria (MMSD 2022).

Despite these challenges, the outlook for lithium mining in Nigeria is promising, with several artisanal miners and large capitalization miners already actively exploring and developing lithium projects in the country (Morgan Stanley, 2015). As the demand for electric vehicles continues to grow, Nigeria is well-positioned to become a significant player in the global lithium market (BloombergNEF, 2022).

According to forecasts, if 100% of the 60 million cars produced annually globally were to be replaced by plug-in hybrid vehicles, lithium carbonate

demand would increase by five times the current production levels (Goonan, 2012). This has led to an increase in junior lithium mining company activity, particularly in Canada and Australia (Morgan Stanley, 2015).

Major financial firms like Morgan Stanley have deemed listed lithium companies as a top investment pick for the next three years due to the growing demand for lithium-ion batteries in electric vehicles and short-term supply shortages (Morgan Stanley, 2016). Artisanal miners and exploration companies are working to fill the current lithium supply shortage, but the development of new lithium operations will come with significant challenges.

Some estimates suggest that if existing lithium producers operate at their current capacities and all expected new producers come online, there will be a surplus of supply (Clarke, 2013). This means that only new deposits with superior project economics will be able to come into production in the coming years.

This paper focuses on one of the key challenges in developing hard rock lithium deposits: the beneficiation methods used to upgrade spodumene ores to produce concentrate suitable for lithium extraction. The paper includes an in-depth review of flotation, dense media separation, magnetic separation, and roasting in spodumene processing, with the objective of identifying areas for improvement and increasing the economic viability of greenfields hard rock spodumene deposits in Nigeria.

1.1 Mineralogy

There are two main economic lithium deposit types: brine and hard rock ore. Brines with commercially viable concentrations of lithium are relatively rare, but extracting and processing brines has lower capital costs and is less energy-intensive than extracting lithium from hard rock ores (Clarke, 2013).

The extraction of lithium from hard rock deposits is a far more complicated and energy intensive process. There are more than 30 lithium bearing minerals; however lithium is mined from five major minerals: spodumene, amblygonite, zinnwaldite, petalite and lepidolite (Bulatovic, 2014). Of these, spodumene is the most prevalent economic lithium bearing mineral (Ober, 1994). It is an aluminosilicate mineral with the chemical formulae $\text{Li}_4\text{Al}_4(\text{SiO}_3)_8$, composed of silica tetrahedral bound laterally through ionic bonding with lithium and aluminum in octahedral co-ordinations (Gasalia, et al., 1987). It is tabular, extremely hard and insoluble in dilute acids (Bulatovic, 2014).

Each crystallographic plane of spodumene has a different number of Al sites, and broken Al-O bonds per Al site. It has been found that the surface potential of spodumene is governed by (110) (cleavage/side planes) and (001) (end planes) crystal planes of the columnar crystal particles, which have the highest density of Al sites in comparison with other crystalline planes (Moon and Fuerstenau, 2003). Figure 1 shows an image of spodumene grains.

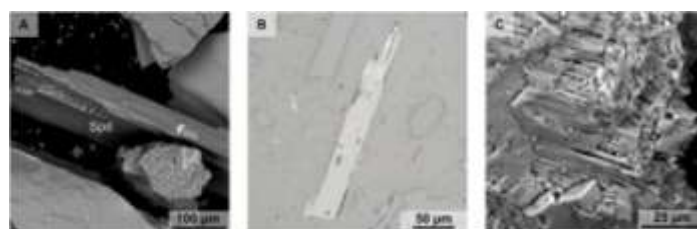


Figure 1. Spodumene grains (Image from SGS Lakefield 2020).

Spodumene is found in pegmatite deposits alongside other silicate minerals like feldspars, micas, and quartz (Norman and Gieseke, 1940; Browning, 1961; Redeker, 1981; Bale and May, 1989; Amarante et al., 1999; Clarke, 2013; Bulatovic, 2014). There are three types of spodumene: phenocrystic spodumene with 0.6-0.9% Fe_2O_3 content, zonal spodumene with 0.01-0.03% Fe_2O_3 content, and spodumene plus quartz aggregates pseudomorphous after petalite with 0.007-0.03% Fe_2O_3 content.

The first type of spodumene is primarily found in economically minable deposits (Heinrich, 1978). Spodumene-bearing pegmatite deposits vary in lithium head grade, ranging from 1% Li_2O in low-

grade deposits to 4% Li_2O in higher-grade deposits (Clarke, 2013).

To determine the mineralogical attributes of spodumene and other Li-bearing minerals, quantitative mineralogy techniques are used. These include QEMSCAN, X-ray diffraction analysis, mineral chemistry analysis using electron microprobe and Laser Ablation (LA) Inductively Coupled Plasma Mass Spectrometer (LA ICPMS). These techniques help determine liberation, grain size, and chemistry of spodumene and other Li-bearing minerals.

1.2 Beneficiation of Lithium Hard Rock Deposit.

The beneficiation of hard rock deposits involving spodumene, a lithium-bearing mineral, can be achieved through various methods, including Dense Media Separation (DMS) (Wills and Napier-Munn, 2005). DMS, also known as Heavy Media Separation (HMS), is a pre-concentration process that separates products of varying density using a heavy medium. This process is commonly used to reject gangue minerals prior to grinding for final liberation (Bulatovic, 2014).

In the context of spodumene beneficiation, DMS can be used to separate spodumene from lighter silicate minerals in a pre-concentration stage. Spodumene has a reported specific gravity between 3.1 and 3.2, while quartz and feldspar have specific gravities between 2.5 and 2.6, and mica has a specific gravity between 2.8 and 3.0 (Redeker, 1979). This makes it possible to separate these minerals using dense media. However, due to the close relative densities, spodumene liberation must be high at larger particle sizes to minimize lithium losses to the float product.

DMS

DMS has been used in various spodumene beneficiation plants, including the Foote Mineral Company and the Lithium Corporation of America (Redeker, 1979). However, due to issues with washing and screening, the DMS feed size was increased, leading to lower lithium recoveries. As a result, all DMS operations at Kings Mountain were decommissioned in the early 1970s, and flotation was solely used to upgrade spodumene.

Laboratory-scale tests have shown that DMS can be an effective means to pre-concentrate spodumene from hard rock operations, with the benefit of less feed to the grinding and flotation circuits and subsequent capital, energy, and operating cost savings (Amarante, 1999). However, the effectiveness of DMS is highly dependent on the degree of spodumene liberation at coarse particle sizes. Poor spodumene liberation will result in significant lithium losses to the float product and negate economic justification for its use.

In addition, other studies have demonstrated the effectiveness of DMS in spodumene beneficiation. For example, Aghamirian et al. (2012) reported that DMS was able to reject 36% of the mass into the float product with lithium losses of only 3.1% at a feed size of -12mm/+0.5mm at an S.G. cut point of 2.7. Similarly, Bulatovic (2014) outlined the successful use of DMS in the processing of ore from Bernic Lake, Manitoba, Canada, where it was possible to reject ~36% of the mass into the float product with lithium losses of only 3.1% at a feed size of -12mm/+0.5mm at an S.G. cut point of 2.7.

Pre-treatment

Ore pre-treatment has been shown to improve spodumene flotation efficiency. Norman and Gieseke (1940) and Manser (1975) found that "cleaning" the mineral surfaces before flotation was necessary for selective flotation. They tested various ores from the United States and found that using Na_2SiF_6 , Na_3PO_4 , Na_2S , or NaOH to "clean" the pulp improved flotation performance. NaOH was found to be the most effective, especially when used in combination with Na_2S .

The practice of cleaning the ore prior to spodumene flotation was used at the Kings Mountain operations, where 225 g/t NaOH was added to the grinding mill to activate spodumene (Redeker, 1981). However, laboratory and pilot plant testing aimed to replace NaOH with a combination of lignin sulphonate and sodium fluoride (Browning, 1961). While this substitution was reported to be successful, NaOH continued to be used as the primary reagent in cleaning (Redeker, 1979; Redeker, 1981).

Bulatovic (2014) described two methods of pulp pre-treatment: conditioning with NaOH at 50-60% solids for 20-30 minutes or treatment with Na_2S under similar conditions. Moon and Fuerstenau (2003) attributed improved spodumene flotation recovery after NaOH treatment to the breakdown of structural silica tetrahedral or re-adsorption of dissolved aluminum species, exposing more aluminum sites on the spodumene surface for collector adsorption.

De-sliming

After pre-treatment, it is common practice to de-slime the ore prior to flotation. De-sliming is necessary to achieve selective flotation of spodumene from its associated gangue minerals. Hydrocyclones are used for de-sliming, and the cut size is determined by the desired size distribution of the flotation concentrate and the spodumene liberation in the ore.

At Kings Mountain, the ore was ground to 100% passing 210 μm , and then 37 μm slimes were removed using hydrocyclones. The slimes were then scrubbed, diluted, and de-slimed again. All slimes were de-slimed at 15 μm , and the plus size material was combined with the +37 μm material for flotation (Redeker, 1981). The slimes contained 7.4% of the weight and assayed 1.43% Li_2O , resulting in 6.5% Li losses.

Flotation

Flotation is a widely used and effective means to upgrade spodumene from pegmatite deposits. The flotation of spodumene will be covered in three sections: flowsheet configuration, reagents, surface chemistry, and the effect of metal cat-ions.

These aspects will be discussed in terms of current practice and new research.

Flowsheet configuration

There are several flotation flowsheet options, the selection of which depends on the nature of the gangue minerals present. These options include:

1. Spodumene flotation only (Bulatovic, 2014; Baarson et al., 1961)
2. Reverse gangue flotation (mica) followed by spodumene flotation (Bulatovic, 2014; Baarson et al., 1961)
3. Spodumene flotation followed by reverse gangue flotation (mica) on the spodumene circuit tailings (Redeker, 1979)
4. Reverse gangue flotation (mica) followed by spodumene flotation and then reverse feldspar flotation from the spodumene flotation tailings (Bulatovic, 2014; Browning, 1961).

Presently, production of spodumene from hard rock deposits is dominated by the Greenbushes operation in Western Australia. While insight can be gained from examination of the details reported on the beneficiation of hard rock spodumene ores from Kings Mountain, NC, and Tanco, Manitoba, it is important to note that these deposits are not currently in operation.

Reagents

Mica Flotation. Typically, the reagents used in reverse silicate gangue mineral flotation are the same regardless if the reverse flotation stage is performed before or after spodumene flotation.

Reverse gangue mineral flotation typically includes mica flotation, to avoid significant quantities of mica in the final spodumene concentrate.

Mica is undesirable in ceramic raw material because it causes brown specks after firing (Norman and Gieseke, 1940). Mica flotation is often conducted in acidic pulp conditions (pH 2-2.5) using H₂SO₄ as a pH modifier and an amine based cationic collector (Browning, 1960;

Bulatovic, 2014). Redeker (1981) also reports use of petroleum sulphonate to float mica, also under acidic pulp conditions. Mica preflotation offers the added benefit or removal of iron silicates and

reducing the overall iron content of the final spodumene concentrate, at least in part. In some instances these minerals may float to some extent with the mica using an amine collector in acidic pulp (Norman and Gieseke, 1940).

There are also collectors that are capable of selectively floating mica from spodumene under

alkaline conditions. Aero 3030C from Cytec is an example. This particular collector is composed of amines, tallow alkyl acetates and ethyl hexanol (Gaied and Gallala, 2011). This may be beneficial as spodumene is also carried out under slightly alkaline conditions and there is no need for major pulp pH modification. Baarson et al. (1961) reported the use of Dextrin as a spodumene depressant in flotation of mica under alkaline conditions.

Feldspar Flotation

In some instances feldspar is floated from the spodumene circuit tailings and sold as feldspatic sand to glass companies. In order to float feldspar from the primarily quartz tailings, hydrofluoric acid (HF) is used to condition the pulp and adjust pH to ~2-2.5. Feldspar is then floated using a tallow amine acetate collector with a 12-14C hydro carbon chain length, kerosene and frother (Redeker, 1981). If there is mica present in the ore, it must be removed prior to feldspar flotation otherwise it will report to the feldspar concentrate, making the product unsuitable for ceramics and glass applications (Norman and Gieseke, 1940). In some cases, it is necessary to separate K-Feldspar from Na-Feldspar as K-Feldspar can contain large concentrations of rubidium (>1%) in its crystal structure, making it more valuable for use in durable ceramic products (Martins et al., 2013). K-Feldspar can be preferentially upgraded by adding NaCl during feldspar flotation. The final tailings from feldspar flotation can be a high grade quartz concentrate with an assay > 98% SiO₂.

Extensive studies have been conducted on the flotation of silicate minerals such as mica, quartz and feldspars, including work by Pradip and Fuerstenau (2005). The details of this flotation process will not be reviewed in great detail in this paper.

Beryl Flotation

the spodumene was floated using a fatty acid collector. The spodumene tailings were then conditioned with sulphuric acid and an amine collector for mica rejection. The mica flotation tailings were then thickened and conditioned with hydrofluoric acid and then washed. The pulp was then conditioned with NaOH and beryl was floated using oleic acid to produce a beryl concentrate assaying 3% Li₂O and 1.57% BeO with 75% beryl recovery (Browning, 1961).

Spodumene Flotation. The following is a comprehensive list of collectors that have been tested on real ores and pure minerals for the flotation of spodumene (Table 1):

Table 1: List of collectors tested on spodumene ores

Tall oil fatty acid (5-7% rosin acid content)	Redeker (1981)
Oleic acid, sodium and ammonium oleate, and different sulphate/ sulphonated/ phosphorated fatty acids	Norman (1940)
Oleic acid	Yu et al. (2015)
Oleic acid	Amarante et al. (1999)
Oleic acid + naphthenic acid	Amarante et al. (1999)
Sodium oleate	Xu et al (2016)
Sodium oleate + dodecyl trimethyl ammonium chloride	Xu et al. (2016)
Dodecylamine	He et al. (2014)
LR15: 62% Oleic acid, 27% petroleum sulphonate, 8% kerosene, 8% pine oil	Bulatovic (2014)
LR17: 61.6% D30LR, 27.7% petroleum sulphonate, 8.2% kerosene, 2.5% pine oil	Bulatovic (2014)
LR19: 62% D30LR, 27% petroleum sulphonate, 9% kerosene, 2% pine oil	Bulatovic (2014)

These collectors, oleic acid and other tall oil fatty acids are consistently used in full-scale operations, although Bulatovic (2014) reported that the LR series mixtures, particularly LR19 which contained 27% petroleum sulphonate, resulted in improved spodumene recovery when compared to oleic acid alone. Amarante et al. (1999) found a mixture of 500 g/t oleic acid, 200g/t naphthenic acid and 3500 g/t of fuel oil to show better flotation performance and selectivity than oleic acid alone when tested on ore from northern Portugal. The majority of these collectors were tested under slightly alkaline pulp conditions (between pH 6.5 and 8.5), with the exception of sulphated, sulphonated and phosphorated fatty acid compounds which were tested in acidic pulp conditions (Norman and Gieseke, 1940). At Kings Mountain operations 700 g/t of tall oil fatty acid was used to condition the ore at 55% solids before rougher-cleaner flotation to produce a concentrate assaying 6.34% Li₂O with 88.4% Li₂O recovery from a head grade of 1.4-1.5% Li₂O. At the Greenbushes operation in Western Australia, spodumene and tourmaline are floated together as a bulk concentrate from -250µm/+20 µm feed using a fatty acid collector and soda ash (Na₂CO₃) at pH 7-7.5 to produce a concentrate assaying 7.5% Li₂O with 0.4% Fe₂O₃ (Bale and May, 1989). New collector mixtures have been tested (Xu et al. 2016), including mixtures of sodium oleate and dodecyl trimethyl ammonium chloride (DTAC) in different ratios with the objective to improve selective flotation of spodumene over other aluminosilicates such as feldspars. Tests were conducted on pure minerals (spodumene and feldspar) and ores from the Jiajika Lithium Mine in Sichuan Province, China. The authors found that a 9:1 optimal ratio of sodium oleate to DTAC, along with NaOH as a pH

modifier and Na₂CO₃ as a feldspar depressant at pH 8-8.6 was most effective. It was possible to increase the spodumene concentrate grade by 0.31% Li₂O with no decrease in recovery. Further, the use of a collector mixture resulted in decreased reagent consumption compared to use of sodium oleate alone. The collector mixture was also less sensitive to a drop in pulp temperature. Moon and Fuerstenau (2003) also investigated the effect of pulp temperature on sodium oleate adsorption on spodumene surfaces which was found to increase with increased temperatures when the critical oleate concentration was exceeded, and decreased with temperature (higher than 35°C) when the oleate concentrate was at starvation levels. This was possibly attributed to initial physical adsorption at low concentrations of collector. Other collectors such as dodecylamine have been reported to produce better spodumene flotation results than oleic acid and other fatty acids (He et al. (2014). However, these studies were not conducted on whole ores or on associated silicate gangue minerals. While spodumene may be highly floatable using amine based While spodumene may be highly floatable using amine based collectors, it may be extremely difficult to achieve selective flotation over other silicates in real ore systems.

Tantalum Recovery.

Tantalum can be a valuable by-product in spodumene ore if the head assay is high enough. Typically tantalum, which is found Ta-Nb oxide minerals, is recovered by gravity separation (Bale and May, 1989). Alternatively, magnetic separation can also be used to recover some tantalum oxide minerals.

Surface Chemistry Considerations

Collector Adsorption. The most significant study conducted on spodumene surface chemistry which relates to flotation was conducted by Moon and Fuerstenau (2003). The authors investigated the relationship between anisotropic crystallographic surface properties and oleate collector adsorption. It was found that oleate was chemisorbed onto aluminum sites at the spodumene surface. Moreover, contact angle measurements were higher on the {110} cleavage plane compared to the {001} crystal plane, indicating that there was preferential collector adsorption on {110} plane. This was credited to the fact that surface Al site on {110} plane has 2 unsatisfied coordinations ideal for oleate ion adsorption. The implication of differential collector adsorption on different planes of the spodumene crystal structure has been identified recently by Xu et al. (2016) who recommended that comminution should be designed to promote the production of {110} cleavage planes for improved flotation. In this study, the flotation behavior and adsorption of sodium oleate was investigated on different size fractions. Of the size fractions tested, spodumene particles between 38 μ m and 45 μ m had the most {110} edges and also demonstrated the best floatability. Finer spodumene particles (<38 μ m) had more {001} basal planes (only one broken Al bond compared to 2 broken Al bonds on the {110} planes) and demonstrated much poorer flotation behavior. These findings are similar to those from earlier work conducted by Gasalia et al. (1987) to study the effect of impact and friction milling on physicochemical properties of spodumene. IR spectroscopy showed AlO_6 vibrations on the spodumene surface at frequencies of 916 cm^{-1} , 860 cm^{-1} , 630 cm^{-1} and 590 cm^{-1} . After shorter grinding times the observed absorbance increased slightly, but after long grind times the bands disappeared or decreased, likely corresponding to a reduction in {110} planes and an increase in {001} planes.

The pH of maximum sodium oleate adsorption was proven to be around pH 8 by Moon and Fuerstenau (2003) through Fourier Transform Infrared spectroscopy studies that showed adsorption at aluminium sites at this pH were strong and irreversible after washing. Further investigation by Yu et al. (2015) found that pH 8 not only corresponded to maximum flotation, but also to the formation of ionic and molecular complexes of oleic acid, suggesting that hydrocarbon chain associated may be partially responsible for good flotation at this pH. The association of the ionic and molecular forms of the reagent resulted in an increase strength of the bond between the COO⁻ group and the aluminum sites at the mineral surface.

Isoelectric Point

Zeta potential measurements conducted on a pure spodumene sample from Kings Mountain, NC by Moon and Fuerstenau (2003) identified the isoelectric point to be 2.3, similar to other silicate minerals. Torres Sanchez et al. (1989) conducted point of zero charge (pzc) measurements by titration on spodumene samples from the San Luis province in Argentina after grinding the pure mineral samples for 0 minutes, 5 minutes, 20 minutes and 50 minutes. It was found that the pzc increased with increasing grind time, likely in part due to increased formation of aluminium oxide at the mineral surface.

Effect of Ions on Spodumene Flotation. Dissolved ions are known to have an effect on flotation of minerals with fatty acid collectors (Nanthakumar et al, 2009). Most recently, the effect of calcium activating ions on the flotation of spodumene was investigated (Yu et al., 2014). Under slightly alkaline pulp conditions, characteristic of those in spodumene flotation circuits with fatty acids, the dominant calcium species were found to be $Ca(OH)^+$ and $Ca(OH)_2$. This corresponds to the maximum floatability of spodumene, and it was suggested that the precipitation of calcium hydroxide on the surface of spodumene was responsible for this activating effect. Wang and Yu (2007) found that both Ca_2^+ and Fe_3^+ in the flotation pulp resulted in spodumene activation. Activation with Ca_2^+ took place at pH 11.7, likely due to the precipitation of calcium hydroxide on spodumene surfaces. Fe_3^+ showed a stronger activating effect than Ca_2^+ , which took place in the pH range between 6 and 9. Moon and Fuerstenau (2003) observed similar phenomena, with ferric impurities leading to activation of spodumene at pH 4 when floated with sodium oleate. These studies neglect to highlight that calcium hydroxide and ferric species are likely to precipitate on the surface of other silicate gangue minerals as well as spodumene surfaces, which can be the cause of concentrate grade dilution. Therefore process water chemistry is likely to have a significant effect on overall flotation performance of spodumene, an area that warrants further study.

Magnetic Separation

Magnetic separation is frequently used to reject iron bearing minerals so that the spodumene concentrate is suitable for use in ceramics and glass applications. Magnetic separation can be conducted at various intensities on different streams in the circuit. While it is most common to perform magnetic separation in the final spodumene concentrate, it can also be carried out on the flotation feed. Magnetic separation on the flotation feed may be beneficial if the objective is to remove large quantities of

amphibole (can be separated at a magnetic intensity of ~10000 Gauss), which would otherwise report to the flotation concentrate. The use of different types of magnetic separation have been reported for this application including HGMS (high gradient magnetic separation) and WHIMS (wet high intensity magnetic separation) (Bale and May, 1989; Jirestig and Forsberg, 1994). Jirestig and Forsberg (1994) conducted magnetic separation testing on spodumene flotation and concluded that effectiveness of magnetic separation is related to particle dispersion in the feed. Recovery to the magnetic fraction improved by 10% when pulp pH was dropped to pH 2 using sulphuric acid for better particle dispersion. It was hypothesized that residual collector can be responsible for flocc formation in the spodumene concentrate. Dropping the pulp breaks the floccs by precipitating oleic acid. By conditioning the pulp at pH prior to magnetic separation the authors were able to improve Li₂O grade of the concentrate by 0.15% with a 0.35% in Fe₂O₃ grade. Lithium losses to magnetic product were reduced by 1.13%.

Roasting

In order to extract lithium from spodumene, the crystal structure of the mineral must be -form (as mined and concentrated) into -form. This is accomplished through the addition of heat, most commonly in conventional resistance heated furnaces at a temperature of 1050°C (Bale and May, 1989; Peltosaari, 2015). Once -form, then the lithium in the crystal structure can be replaced with sodium or hydrogen ions under high temperature or high pressure conditions to eventually (by means of lithium sulphate) produce a final product of lithium carbonate or lithium hydroxide. The details of this process are not covered in this review. During the heating process particles first undergo a size reduction and then expansion followed by breaking apart, resulting in a reduced P80 and specific gravity after roasting. A study of spodumene from Greenbushes transformation by conventional heating (muffle furnace) showed that structural changes were observed in the spodumene crystal after heating at 950°C for 30 minutes. After heating longer than 10 minutes at 1100°C, com and spodumene occurred. This corresponded with volumetric expansion and a concentrate colour change from beige to white (Salakjani et al., 2016). The roasting process is complicated by a large feed size distribution (as can be the case when both DMS and flotation concentrates are produced) and by impurities in the concentrate. In particular, iron bearing silicate minerals can be quite problematic as they tend to soften at high temperature and cause agglomeration of spodumene particles during the roasting process.

Novel research in this area includes investigation into the use of microwave heating as an alternative to conventional heating. Initial results from work conducted by Peltosaari et al. (2015) showed that for spodumene, heating time was reduced significantly when using a microwave compared to conventional heating. The potential energy and cost savings associated with microwave heating are not clear at this time.

II. CONCLUSION

The extraction of lithium from hard-rock spodumene deposits is hindered by outdated and complex beneficiation methods. These methods have seen minimal advancements in recent decades, underscoring the need for innovative solutions. To address this challenge, researchers should focus on developing efficient comminution circuits, selective reagent mixtures, and innovative roasting techniques or alternatives. By optimizing these processes, energy consumption can be significantly reduced, and lithium recovery increased. These advancements will be critical in unlocking additional hard-rock lithium deposits globally, supporting the transition to a low-carbon economy and meeting the escalating demand for lithium-ion batteries and renewable energy technologies.

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