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Beneficiation and concentration of feldspar from syenite ore in Medina, Saudi Arabia for industrial utilization

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Abstract: The objective of this study was to reduce the contents of iron and titanium heavy minerals of feldspar from Medina syenite ore by a combination of magnetic separation and flotation to obtain the commercial scale of feldspar concentrate for glass and ceramics industries. For the first time, a process flowchart was provided in the light of this study to produce a high-quality K-feldspar product from syenite ore, which meets the requirements of feldspar for glass and ceramics productions. The results reflect that the best performance separation of iron and titanium contents was produced by a dry magnetic separator at 16.000 gauss. The produced feldspar concentrate by magnetic separation yielding 0.54% Fe_2O_3 with 87% Fe_2O_3 recovery and 0.57% TiO_2 with 16% recovery. The flotation tests were performed on the non-magnetic fraction of the syenite ore. In this stage, the most effective for removal of Fe_2O_3 and TiO_2 from syenite ore was obtained at a 300 g/ton dosage of a mixture of Aeromine 3030C and Aeromine 801 + Aeromine 825 as a collector in an acidic medium (pH 3). The final feldspar concentrate with 0.07% Fe_2O_3 and 0.06%TiO_2 grades was obtained with 89% Fe_2O_3 recovery and 86% TiO_2 recovery. The commercial scale of feldspar concentrate from syenite ore can meet the desired specification of grades 1 and 2 for glass, porcelain, and ceramics industries.

Keywords: syenite, dry magnetic separation, floatation, grade, recovery

1. Introduction

Syenite is an intrusive igneous rock of variable color but usually light in color, characterized by the phaneritic texture of medium to coarse-grained which belongs to the alkali series of intermediate plutonic rocks (Gougazeh et al., 2018). Alkali feldspar (e.g., orthoclase) is the major mineral component of syenite, total feldspar content is > 65% and usually lacking quartz (< 5%) with minor mica, augite, hornblende, and magnetite (Ernst, 2014). Plagioclase can also be present (< 10%). Titanite is a common accessory mineral.

Alkali feldspar forming the majority of most syenitic rocks is usually intergrown with sodium-rich plagioclase feldspar (usually oligoclase). This feldspar intergrowth is named perthite (Gougazeh et al., 2018) and this is why syenite is a more common rock type than alkali feldspar syenite which contains almost no plagioclase. Plagioclase may appear in syenite rocks as well as perthitic, alkali feldspar separate phases. Dark mica biotite and amphibole hornblende are the usual mafic components. Common accessory minerals are zircon, apatite, sphene, magnetite, and ilmenite (Celik et al., 2001; Orhan and Bayraktar, 2006; Vorontsov et al., 2021).

Syenite is used as a source for Al_2O_3, K_2O, and Na_2O, in the ceramic, porcelain, and glass industry. These oxides are the most components of feldspar. In ceramics production, feldspar is the second most important component after clay. Feldspar does not have a strict melting point, over a range of temperatures, the feldspar melts gradually. This significantly motivates the melting of clay and quartz, and throughout proper mixing, permits the use of this significant step of ceramic manufacturing. A glassy phase is formed at low temperatures by using feldspar as fluxing factors. It improves the strength, rigidity, and durability of the ceramic body, enhances the crystalline phase of other components, softening, melting, and moisturizing other batch components as well as the source of alkalis and alumina in glazes. In the glass industry, the feldspar is a significant ingredient as well as

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valuable raw material, as it works as a fluxing factor, which reduces the quartz melting temperature and helps control the glass viscosity (Karaguzel, 2010; Lewicka, 2010). Alkaline content works in feldspar as a flux, decreases the temperature of melting glass batch as well as decreases production costs. Feldspars are also used as fillings and extensions in applications such as paints, plastics, and rubber (Vidyadhar et al., 2002). Useful properties of the feldspars include good disperses, high chemical inactivity, stable pH, high corrosion resistance, low viscosity when loading high filler, an attractive refractive index, and frost resistance (Hacifazlioglu et al., 2012).

The upgrading and concentration processes of feldspars in Russia, Norway, Italy, Canada, China, and Turkey are conducted by flotation technique (Bayat et al., 2007; El-Salmawy et al., 1993; Gougazeh, 2006; 2022; Gulsoy et al., 2005; Hanumantha, 2007, Karagüzel, 2010, and Karagüzel and Obanoglu, 2010; Vidyadhar, 2007). The flotation of the colored impurities in the feldspar ore was floated with multi-stage flotation. All flotation tests were carried out with dosage changed from 100 to 600 g/t and at an acidic medium with a pH of ≈ 3. In the first stage, mica floatation, and in the second stage, heavy (iron and titanium bearing) minerals floatation was applied. First, Micaceous minerals were floated with Aero 3030C cationic collector at acidic medium at pH 3 and the remaining ore was washed to remove the stains of the collectors from the mineral surfaces. Second, heavy mineral contents (iron- and titanium-bearing impurities) in an acidic medium (pH 3) were floated with the mixture of Cyanamid Aero promoter 801 + 825 + 830 at a ratio of 1: 1: 1 at pH 3 (Abouzaid and Negm, 2014; Burat et al., 2006; Gougazeh, 2022, Gulsoy et al., 1994).

Burat et al., (2006) investigated the effect of magnetic separation and flotation to reduce the coloring iron impurities of the final products of feldspar from syenite ore to meet the desired specification for glass and ceramic grades. Ibrahim et al., (2002) conducted studies using a dry magnetic separation technique to beneficiate some Egyptian nepheline syenite and the resulted concentrates ranging from 0.5 to 0.7% Fe_2O_3, which could never lead to a saleable concentrates products, however the processing of the magnetic separation concentrate by flotation produced in a final product of high quality assaying 0.09% Fe_2O_3, 23.58% Al_2O_3 and 16.47% Na_2O + K_2O (Ahmad, 2011; Abouzaid and Negm, 2014). The Fe_2O_3 content was minimized to 0.10% by a combination of magnetic separation and the conventional flotation cell, whereas TiO_2 content wad reduced to 0.02% by the conventional flotation cell (Hacifaziloglu et al., 2012).

The Fe_2O_3 and TiO_2-bearing minerals have been removed by a combination of magnetic separation and flotation techniques (Bayat et al., 2006; Burat et al., 2007; Silva et al., 2019; Silva et al., 2015; Zhang et al., 2018). The Fe_2O_3 content of a nepheline syenite ore was reduced from 0.19 to 0.09% by using flotation followed by dry magnetic separation (Burat et al., 2007). The Fe_2O_3 grade of a Brazilian foyaite was reduced from 3.14 to 0.60% by using magnetic separation after flotation. These studies, however, did not investigate and evaluate the effects of parameters of concentration that may upgrade the quality of the final concentrate such as magnetic field on magnetic separation and collector dosages on flotation.

The common components of feldspar ores are iron and titanium oxides, which affect the feldspar color and reduce its purity and quality for use by the ceramic, porcelain, and glass industry. However, the economic assessment of the final feldspar product is generally defined by iron and titanium content. In terms of cost and accessibility, magnetic separation seems to be the most applicable method for improving the quality of feldspars. Based on the mineralogical characteristics, the flotation method is substantially desired because magnetic sensitivities of Ti-minerals such as rutile, sphene and anatase are very low and magnetic separators in this field be able to achieve effective separation down to a definite particle size. For removal of the unwanted impurities in feldspars, the reverse flotation is still the most significantly and widely used concentration method (Hacifaziloglu et al., 2012).

In this study, syenite ore is found in the Jammah area of the western part of Medina, Saudi Arabia (Fig. 1). The beneficiation, pre-concentration and upgrading techniques of the syenite ore (feldspar ore) from Medina are discussed here in detail as a laboratory scale which is a kind of new approach. The first attempt to upgrade feldspar from granitic deposits of Medina as a semi processing scale was made by Gougazeh (2022). This study clearly shows the vital role of beneficiating and upgrading the Medina feldspar from Syenite ore to meet the specification of ceramics and glass industries to increase its economic value. This study is concerned with the characterization and beneficiation studies of this ore. The main characteristics of ore investigated are mineral and chemical analysis. In addition, its economic interest is still to be assessed. Data collected from characterization studies will be the outline for the beneficiation process of utilizing syenite raw material. The present work intends to fill this lack of information and reports on beneficiation methods for opening up syenite deposits as feldspar source and specifies the requirements to be met feldspar products for varying industrial applications. The main objective of this study is to investigate the possible use of a combination of magnetic separation and flotation techniques in the recovery of feldspar from syenite ore with higher recoveries to assess its economic potential to be used as raw material in glass and ceramic industries.

2. Materials and methods

2.1. Material

A fresh syenite sample, about 20 Kg, was collected from the Medina region/Saudi Arabia (Fig. 1). The most significant syenite deposit was exposed in Jammah area in the western part of Medina (Gougazeh et al., 2018). As evident from the microscopic examinations of the thin sections, the syenite ore is mostly dominated by the alkali feldspar (orthoclase) with small amounts of plagioclase (oligoclase), quartz, and mica. It is distinguished by perthitic texture [intergrowth of alkali feldspar (orthoclase) with sodium-rich plagioclase (oligoclase)] (Gougazeh et al., 2018).

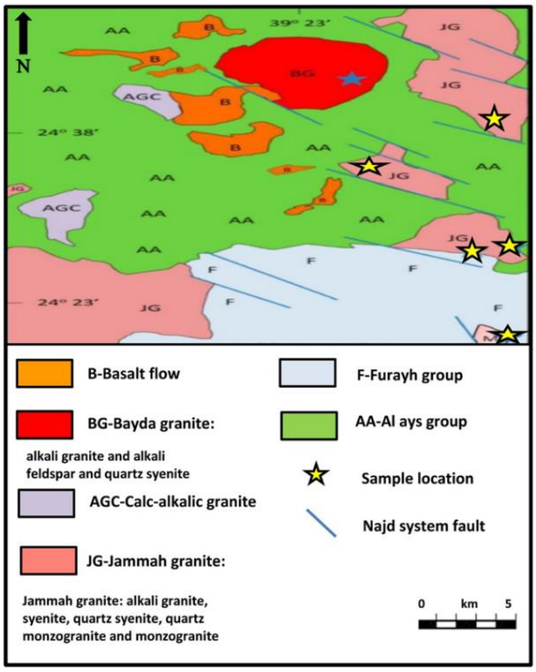

Fig. 1. Simple location map of representative samples (modified after Gougazeh et al., 2018)

2.2. Characterization methods

The mineralogical phases of syenite ore were determined by X-ray diffraction (XRD) studies. The XRD studies of the ore were carried out using the model, Bruker AXS D4 ENDEAVOR, and X-ray diffractometer at Cu Kα radiation at 40 kV and 40 mA. The diffractograms were recorded from 3 to 80^{o} 2θ with a scan speed of 15 s/step to identify different mineral phases present in the ore sample. The diffraction data were analyzed using the Stoe WinXPOW software package. X-ray fluorescence (XRF) (Philips PW1400 Wavelength Dispersive Sequential) was used for the chemical analysis of the feed sample and concentrations of products. Fe_2O_3 and TiO_2 were examined throughout the concentration testes as an indication of the efficiency of iron and titanium oxides removal in the produced concentrates. At the optimum separation and concentration conditions, all the important chemical compositions were analyzed for the final concentrates. The grain size distribution was carried out by wet sieving at 2000, 500, 250, 150, 90, 53, and 38 μm.

2.3. Beneficiation studies

As part of the separation experiments through the magnetic separation process, the syenite ore sample was first crushed to less than 4 mm in size by a combination of jaw and cone crushers in a closed circuit with a sieve of 0.250 mm. The oversize (+ 0.250 mm) fraction was also wet ground to less than 250 µm in a carbon steel mill at 82 rpm and was then classified and deslimed by wet screening through a mesh number of 400 (- 38 µm). The presence of slimes makes harmful effects on the results of flotation tests such as recovery, selectivity, and consumption of the chemical reagents. Particles in the size range of – 250 + 38 µm (where the feldspar is naturally concentrated), were fed into a high-field dry magnetic separator which contains 18000 gauss (magnetic separation was performed by the Frantz isodynamic separator tool). The syenite ore sample was inserted into a high-field dry magnetic separator under the operating condition (Roll speed 30 revolutions per minute, current coil starts at 3.7 ambers and ends at 2.8 ambers, vibrating control 30 Hz). The non-magnetic fraction was analyzed by XRF.

Syenite ore processing techniques such as crushing, grinding, screening, de-sliming, magnetic separation, and multi-flotation are shown in Fig. 2. The coloring materials such as iron and titanium oxides can be reduced and removed to upgrade the purity and quality of feldspar products through high-field dry magnetic separation and flotation techniques.

The aim of magnetic separation tests was to produce the non-magnetic alkali feldspar (orthoclase) from the syenite ore. Magnetic impurities (Fe_2O_3 + TiO_2 contents) were performed on the feed size fraction (-250 + 38 µm) using different field intensities of 6.000, 10.000, 14.000, 16.000, and 18.000 gauss. 500 grams of feeding fraction were used and placed in a feeding chamber, which feeds the material on a conveyor belt to the magnet. A sample at the end of the magnet allowed different arrangement settings to control the magnet effect of a larger feeding area. Table 2 presents the chemical composition of the non-magnetic fractions produced. The non-magnetic fraction was then used as a feed for the next concentration step as the flotation process.

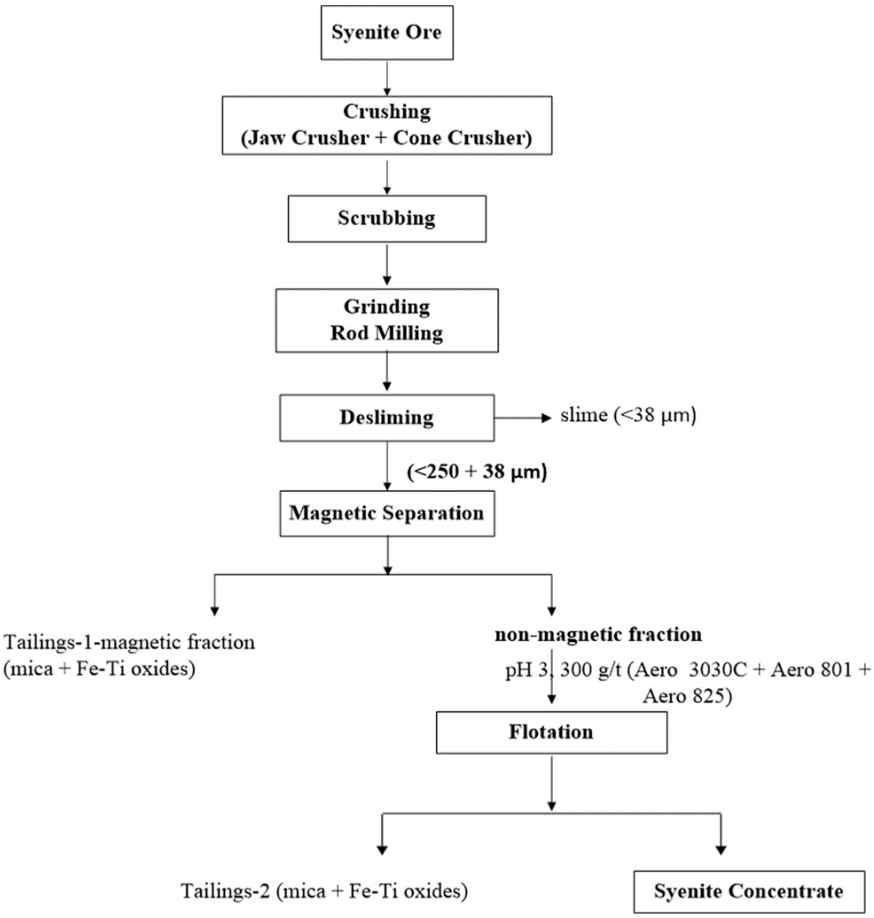

Fig. 2. Beneficiation flowchart of syenite ore

In this study, Flotation experiments were conducted using a 2-liter Denver D12 laboratory-type flotation cell. The flotation of mica and heavy minerals (Fe-and Ti-oxides) was performed on the non-magnetic fraction at 24°C room temperature to produce the alkali feldspar products with a very low content of iron and titanium impurities to meet the requirements of the ceramic and porcelain industry. A mixture of collectors (AERO 3030C and AERO 801 + AERO 825) was used at a ratio of 1:1:1 in an acidic medium at pH 3. The pH was successfully modified by H_2SO_4. Bayat et al., (2006) obtained that for flotation of feldspars, combined application of the mentioned AERO's mixture showed better than the utilization of these collectors alone. They are effective in increasing grade, recovery and throughput with corresponding lower modifier costs. The conditioning stage was performed with a pulp ratio of 30% and 5 min at an impeller speed of 1200 rpm and an aeration rate of 5L/min. The flotation experiment was conducted at an impeller speed of 1200 rpm.

3. Results and discussion

3.1. Characterization of raw materials

Results of the major elements of the syenite raw material were obtained by XRF analysis and summarized in Table 1. The contents of impurities as indicated by the chemical result were 3.45% Fe_2O_3 and 0.68% TiO_2. The sample has K_2O and Na_2O contents of 7.53% and 5.42%, respectively reflecting the presence of high amounts of alkali feldspar [orthoclase ($KALSi_3O_8$)]. The chemical analyses of the syenite ore (Table1) are in agreement with the mineralogical composition. The LOI value is too low due to the low content of carbonate and the absence of organic matter in syenite ore (Table1). X-ray diffraction analysis (Fig. 3) of syenite raw material showed that it was mostly composed of orthoclase ($KALSi_3O_8$) with minor amounts of microcline ($KALSi_3O_8$), oligoclase (Na,Ca)[(Si,Al)Si_2O_8], and quartz (SiO_2). The syenite ores are principally composed of silicate minerals. The results of the wet sieving method (Fig. 4) of the investigated syenite sample show that about 86% is below the optimum liberation size fraction of 250 μm, about 6% is below 38 μm and about 80% is between 250 and 38 μm. This indicates that about 80% of the Medina syenite is in a suitable size range after wet sieving to be beneficiated and concentrated by magnetic separation and flotation techniques.

Table 1. Major oxide composition (%) of the studied syenite raw material

SiO_2	TiO_2	Al_2O_3	Fe_2O_3	CaO	MnO	MgO	Na_2O	K_2O	P_2O_5	LOI*	Sum
64.21	0.68	16.27	3.45	0.62	0.02	0.48	5.42	7.53	0.13	0.71	99.52

*LOI: Loss on ignition was determined using a muffle furnace at 1000°C for 90 min

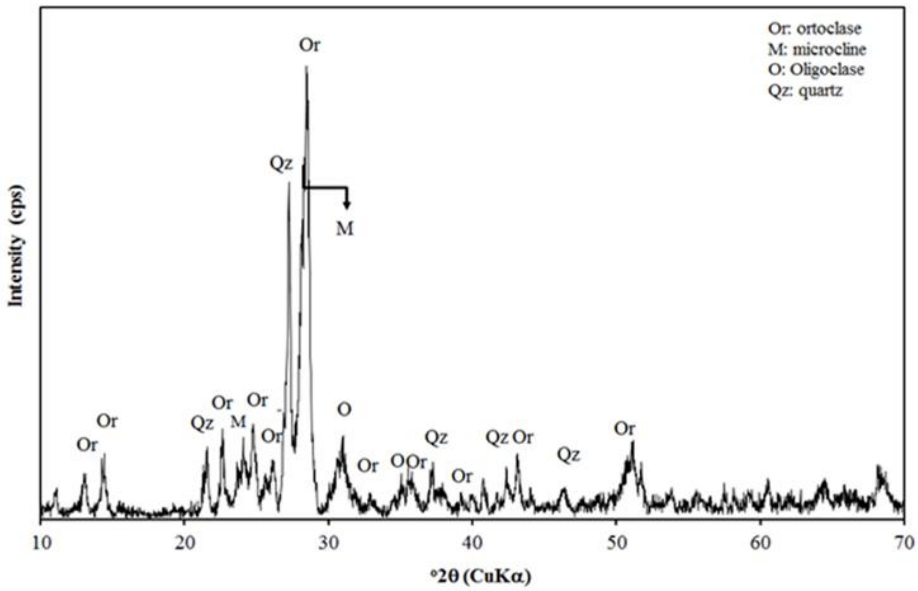

Fig. 3. XRD pattern of raw syenite ore, Medina, Saudi Arabia

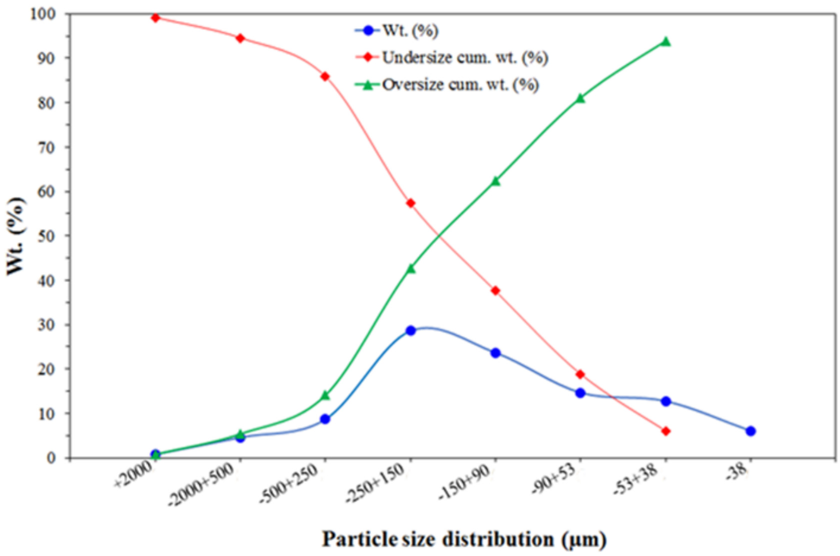

Fig. 4. Particle size distribution for raw syenite ore, Medina, Saudi Arabia

3.2. Magnetic separation results

A dry magnetic separator with high field intensity (18.000 gauss) was used to decrease the discoloring of iron and titanium oxides (Gougazeh, 2022). A different magnetic field intensity was conducted on the obtained fraction (-250+38 µm) from the crushing, grinding, and screening processes. The deslimed fraction (feed) was examined by high intensity magnetic separation. The influence of various intensities 6, 10, 14, 16 and 18 kgauss were examined (Fig. 5). The obtained product of low intensity magnetic separation was subjected again by growing the current intensity. gotten of non-magnetic fraction from first low intensity. The obtained of final non-magnetic product was then fed to the flotation process. Fig. 5 shows the results of magnetic separation experiments. The optimum separation of Fe_2O_3 content was obtained at a magnetic intensity of 16.000 gauss. As clearly shown in Fig. 5, the results indicated that the contents of Fe- and Ti- oxides were reduced to 0.54% and 0.57% with a recovery of 87% and 16%, respectively. The magnetic separation results reflected poor effecting for the removal recovery of TiO_2 due to the very low magnetic susceptibility when a magnetic field is applied.

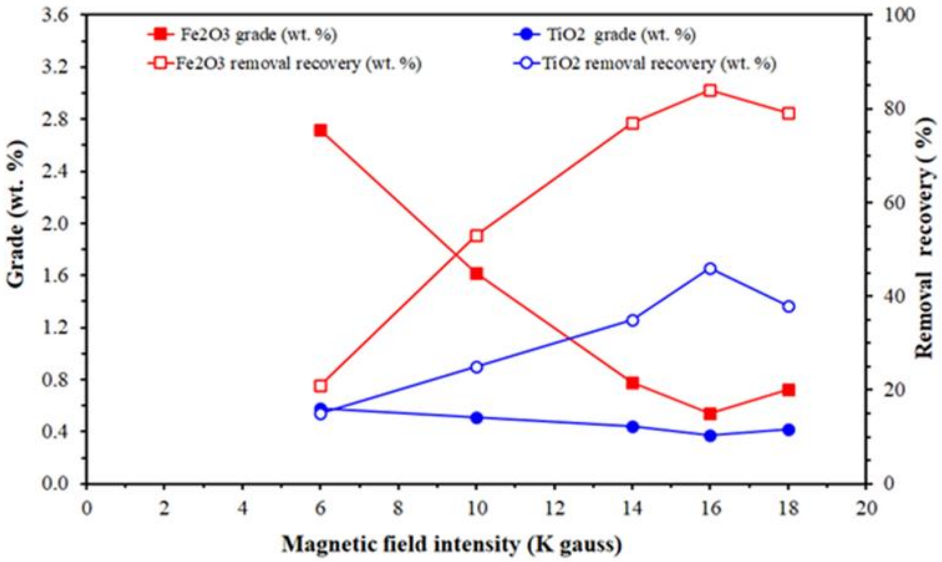

Fig. 5. Effect of the field intensity on the performance of the dry magnetic separator for reducing Fe_2O_3 and TiO_2 contents and their removal recoveries in non-magnetic concentrate of the feed fraction (-250+38 µm) from Medina syenite ore

The non-magnetic fraction contained the highest product of alkali feldspar (orthoclase and microcline) is presented in Table 2.

Table 2. Chemical composition (%) of produced syenite product after magnetic separation

SiO_2	TiO_2	Al_2O_3	Fe_2O_3	CaO	MnO	MgO	Na_2O	K_2O	P_2O_5	LOI*	Sum
64.65	0.57	17.82	0.54	0.32	0.02	0.29	5.47	9.25	0.12	0.62	99.47

*LOI: loss on ignition

3.3. Flotation results

The flotation experiments were conducted on the non-magnetic concentrate. As shown in Table 2, the chemical analysis of this concentrate is composed of 17.82% Al_2O_3, 9.25% K_2O, 5.27% Na_2O, 0.54% Fe_2O_3, and 0.57% TiO_2. The dry magnetic separation was conducted on the fraction (-250+38 µm) with the best performance of magnetic separation obtained at a field intensity of 16.000 gauss. The optimum conditions of the flotation experiments are presented in Table 3.

Table 3. The operating parameters of the flotation tests

Parameters	Components
particle size	-250 + 38 µm
cell volume	2 Liter
pulp density	25% solid by weight
pulp pH	3
frother types	pine oil (20 g/t)
collector type	Aero 3030 & Aero 801 + Aero 825
collector concentration	100, 150, 200, 250, 300, 350, & 400 g/t
flotation speed	800 rpm
conditioning speed	1200 rpm
conditioning time	7 min
flotation time	3 min

The iron and titanium minerals of the non-magnetic fraction (-250+38 µm) of syenite ore were floated in 25% solid by weight with a mixture collector of Aero 3030C, Aero 801, and Aero 825 promoters with a 1:1:1 ratio in an acidic medium at pH 3.

The purity and quality of syenite concentrate were affected by the collector dosages of a mixture of Aero 3030C and Aero 801 + Aero 825. The effect of mixture dosages of the collector on the Fe_2O_3 and TiO_2 content and these removal recoveries are presented in Fig. 6. It was found that a dramatic decrease in Fe_2O_3 +TiO_2 content, as well as a significant increase in removal recoveries of these colored impurities in the feldspar concentrate with the increase of the content of the reagent mixture. As clearly shown in Fig. 6, the best performance of flotation results was obtained at 300 g/t dosage which produced a high-quality K-feldspar concentrate from Medina syenite ore containing 0.07% Fe_2O_3 and 0.06% TiO_2 with 89% and 86% removal recovery for Fe_2O_3 and TiO_2, respectively (Table 4).

The comparison of the weight percentage of Fe_2O_3 and TiO_2 removal recovery obtained by magnetic and flotation methods is given in Fig. 7. As shown in Fig. 7, a total of 89% Fe_2O_3 and 86% TiO_2 were removed by flotation method and alkali feldspar concentrate assaying 0.07% Fe_2O_3 and 0.06% TiO_2 was obtained, whereas the magnetic separation at a field intensity of 16.000 gauss produced a feldspar concentrate containing 0.54% Fe_2O_3 and 0.57% TiO_2 with a removal recovery of 84% Fe_2O_3 and 16% TiO_2. It is noticed that both upgrading processes (magnetic separator and flotation) revealed the similar performance separation with respect to Fe_2O_3 removal. The obtained results of magnetic separations and flotation tests indicate that the content of Fe_2O_3 was found at 0.54% and 0.06% with removal recovery at 84% and 89%, respectively, while the contents of TiO_2 are different. As shown in Fig. 7, the flotation process showed the high performance in respect to TiO_2 removal with 86% removal recovery, while the magnetic separation exhibited poor performance for

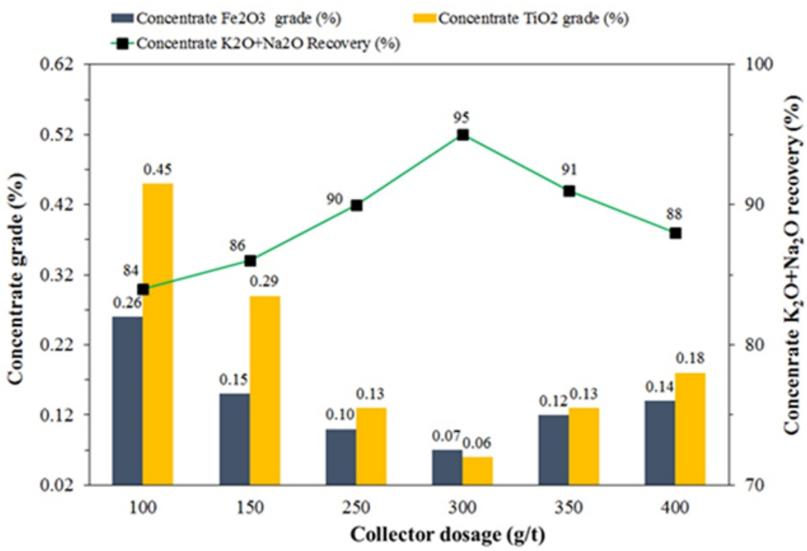

Fig. 6. Effect of collector dosage on concentrate grade and removal recovery of Fe_2O_3- and TiO_2-bearing minerals

Table 4. Chemical composition (%) of produced syenite concentrate after flotation

SiO_2	TiO_2	Al_2O_3	Fe_2O_3	CaO	MnO	MgO	Na_2O	K_2O	P_2O_5	LOI*	Sum
64.65	0.06	19.93	0.07	0.11	0.02	0.10	4.01	11.71	0.10	0.42	100.18

*LOI: loss on ignition

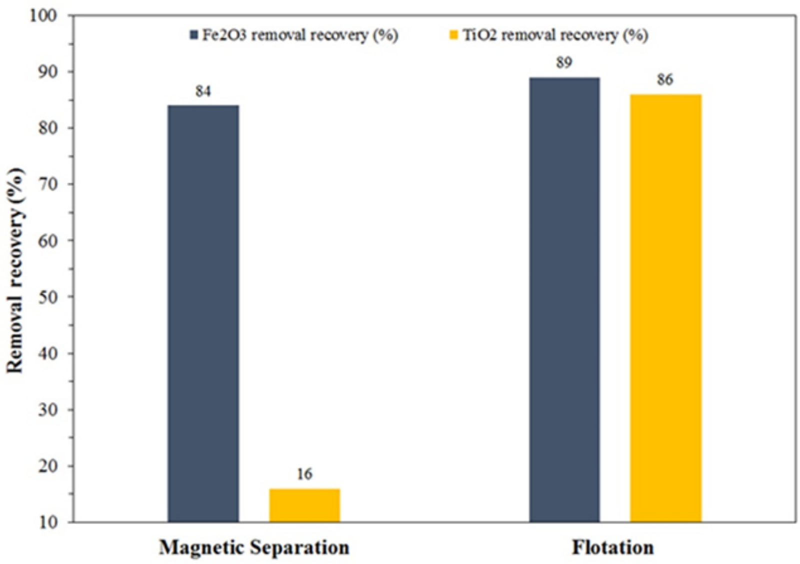

Fig. 7. Comparison of weight percentage of Fe_2O_3 and TiO_2 removal recovery from feldspar by magnetic separation and flotation methods

the removal of TiO_2 with 16% removal recovery. The diamagnetic minerals forming the TiO_2 content such as anatase and/or rutile and sphene have low magnetic susceptibility. The magnetic separator has not captured these minerals and has not removed or enough reduced them into the non-magnetic concentrate. The obtained results indicated that the highest efficiency was produced by flotation tests, and the very poor efficiency was produced by the magnetic separator.

The relationship between the alkaline content (K_2O + Na_2O) and the recovery of alkali feldspar concentrate is shown in Fig. 8. As shown in Fig. 8, the obtained results of the flotation test indicated that the feldspar concentrate was achieved with a high alkaline content of 15.72% (K_2O and Na_2O) and 96% K_2O and Na_2O recovery with the use of a 300 g/t collector mixture of Aero 3030C and Aero 801 +

Aero 825 at pH 3. The requirements of feldspar grades for glass and ceramics industries are given in Table 5. As clearly shown in Table 5, a high- quality and marketable feldspar concentrate with very low undesirable mineral content (Fe_2O_3 +TiO_2) and high alumina content as well as high alkaline content (K_2O + Na_2O) was obtained from medina syenite ore. Finally, the produced feldspar concentrate was achieved the desired values of high-quality feldspar of the grades 1 and 2 of the Indian specifications (IS 9749) of feldspar for glass and ceramics industries.

Table 5. Requirements of feldspar grades for glass and ceramics industries (IS 9749)

Components (wt. %)	Grade 1	Grade 2	Grade 3	Medina syenite concentrate
SiO_2 (Max)	67	67	68	64.65
Al_2O_3 (Max)	17-20	17-21	17-21	18.93
SiO_2/Al_2O_3	3.4-3.6	3.4-3.6	3.5-3.8	3.41
Fe_2O_3 (Max)	0.08	0.1	0.2	0.07
TiO_2 (Max)	0.06	0.08	0.1	0.06
CaO + MgO (Max)	0.75	1	1	0.49
K_2O	12	10	9	11.71
Na_2O	4	4	6	4.01
*LOI (Max)	0.6	0.6	0.8	0.42

*LOI: loss on ignition

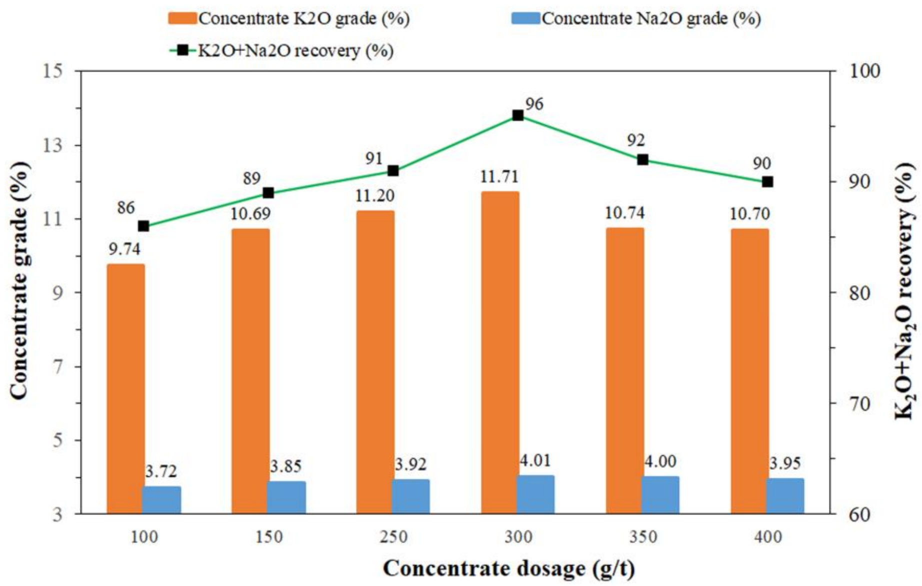

Fig. 8. Effect of the collector dosage on K_2O + Na_2O content and the recovery of feldspar

4. Conclusions

In this study, the syenite concentrate was obtained by a combination of magnetic separation and flotation techniques with the grades of 0.07% Fe_2O_3 and 0.06% TiO_2 using a promotor mixture of AERO 3030C and AERO 801 + AERO 825 at 300 g/t with the recoveries of 89% Fe_2O_3 and 86% TiO_2. In all tests, no additional frother was added due to the additional frothing function of the AERO 801 and AERO 825. The results reflected that a higher quality and recovery of feldspar were obtained when a mixture of theses collectors were used. These tests were conducted on the -250 + 38 µm size fraction. As a result of flotation tests, TiO_2 content in the non-magnetic fraction was reduced from 0.57% to 0.07%, and the TiO_2 content was reduced by magnetic separation from 0.68% to 0.57%. Based on the results of this study, this status is due to that the Fe_2O_3 oxide has magnetic susceptibility, but TiO_2

mineral has low magnetic susceptibility. As a result of the magnetic separation and flotation experiments, the amounts of both K_2O and Na_2O grades in the syenite concentrate (alkali feldspar concentrates were increased to 15.73% with a recovery of 96% of feldspar concentrate. The feldspar concentrate containing low silica 64. 65% SiO_2, high alumina 18.93% Al_2O_3, high alkaline content (11.71% K_2O and 4.01% Na_2O), very low iron and titanium with 0.07 and 0.06%, respectively. Therefore, the result showed that the obtained feldspar concentrate from the studied syenite ore can be reached the grades 1 and 2 of the industrial requirements and specifications for ceramic and glass industries.

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