JEE Journal of Ecological Engineering

Journal of Ecological Engineering 2022, 23(6), 271–277
https://doi.org/10.12911/22998993/147834
ISSN 2299–8993, License CC-BY 4.0

Received: 2022.03.06
Accepted: 2022.03.30
Published: 2022.04.20

# Beneficiation and Upgrading of Low-Grade Feldspar Ore in Medina, Saudi Arabia

Mousa Gougazeh[1]

[1] Natural Resources and Chemical Engineering, Tafila Technical University, P.O. Box 179, 66110, Tafila, Jordan
e-mail: dr_eng_mhag@yahoo.com

**ABSTRACT**

Large reserves of feldspar ore deposits are found in the alkali granite rocks at Al-Madinah province, Saudi Arabia. Magnetic separation and flotation tests were used in order to achieve the aims of this study which are: reduce the iron and titanium contents of Medina feldspar ore, which impart color and decrease the feldspar quality, as well as produce a high-quality feldspar concentrate, which meets the commercial grade of the raw material specifications for the ceramics and glass industry. The obtained results from this study showed that the efficient separation of Fe- and Ti-bearing minerals could be achieved by a combination of the dry high-intensity magnetic separator at 14.000 gauss and the direct cationic flotations under 500 g/ton dosage of Aero 801 + Aero 825 + Aero 830 mixture in an acidic medium at pH 3. The feldspar concentrate was produced with 65.18 wt.% $SiO_2$, 19.02 wt.% $Al_2O_3$, 0.06 wt.% $Fe_2O_3$, 0.09 wt.% $TiO_2$ 9.09 wt.% $K_2O$ and 6.01 wt.% $Na_2O$ grades, which meet the commercial scale of feldspar.

**Keywords:** discolored impurities, feldspar concentrate, floatation reagents, magnetic separation.

## INTRODUCTION

Feldspar is the most important single group of rock-forming silicate minerals, containing sodium, calcium, potassium, or barium (Neuendorf et al., 2005). The most common members of the feldspar group are the plagioclase (sodium-calcium) feldspars and the alkali (potassium-sodium) feldspars (Deer et al., 2001). There are four chemically district groups of feldspar: potassium feldspar ($KAlSi_3O_3$), sodium feldspar ($NaAlSi_3O_8$), calcium feldspar ($CaAlSi_3O_8$) and barium feldspar ($BaAl_2Si_3O_8$) (Heyes et al., 2012). A variety of names are given to feldspar minerals, depending on their composition. Granites and pegmatites are sources of soda and potash feldspar which find extensive use in the glass, ceramics, and filler industries. Feldspar is a source of alkalis and alumina in the glass and ceramics industries that make the products more transparent. About 90% of produced feldspar is used by the glass and ceramic industries. Soda feldspar finds the most application in glassmaking, while potash feldspar is preferred in the ceramics industry. Feldspars play an important role as fluxing agents in ceramic and glass applications and are also used as functional fillers in the plastic, paint, rubber, and adhesive industries. The economic importance and value of industrial minerals is continually increasing, and the interest in industrial mineral commodities is increasing. This resurgence has emphasized the need to increase the efforts to study, evaluate and upgrade the feldspar ore deposits of Al-Madinah, KSA.

The overall goals of this study were to produce feldspar containing a high percent of the total sodium and potassium oxides and reduce the percentage of iron and titanium oxides. The feldspar needs to be upgraded in order to meet the commercial specifications. There are large quantities and sufficient reserves of feldspar ore in the Al-Madinah region in the western part of Saudi Arabia with good physical and chemical properties (Gougazeh et al., 2018). The study area has a good infrastructure and is favorably located for the supply of raw materials to the industries in Saudi Arabia. Naturally, the feldspars deposits in this area are both sodium and potassium feldspars with the associated minerals such as muscovite, biotite, and heavy (iron and titanium bearing) minerals. No attempt has been made before to obtain separate feldspar products from Al-Madinah feldspar ore. The aims of this study are to extract feldspar ore and process it using modern technology to obtain a usable high-quality industrial feldspar product which is able to meet the desired specifications for industrial applications, as well as iron, titanium separation, and silica associated with this raw material and proper production process, such as crushing, grinding, sieving, magnetic separation, and flotation.

## MATERIALS AND METHODS

### Materials

The representative feldspar ore sample (weighing about 30 Kg) was obtained from granitic rocks in the Medina region / Saudi Arabia (Gougazeh et al., 2018).

### Characterization methods

X-ray diffraction (XRD) performed with the model (Bruker AXS D4 ENDEAVOR) was used for mineralogical analyses. X-ray fluorescence (XRF) Philips PW1400 Wavelength Dispersive Sequential Spectrometer was employed to analyze the major oxides of the feed sample the concentrate during and in the final stage of the beneficiation and upgrading processes.

### Laboratory beneficiation tests

The representative feldspar ore was firstly crushed to below 2 mm in size by jaw and hammer crushers, in a closed circuit with a 0.3 mm sieve. The rest of the plus 0.3 mm fraction was also wet ground to below 300 µm in a porcelain ball mill at 82 rpm and then classified as well as deslimed by wet sieving through 325 mesh size (- 38 µm). The particles of – 38 µm were separated as slimes, which amounted to about 16 wt.%. Before starting work with magnetic separation experiments, and according to the nature of the feldspar ore in this study, the particle size or the fine materials that are below 38 microns should firstly be deslimed. The presence of these slime materials creates major problems and affects the efficiency of the magnetic separation process in terms of energy consumption as well as affects the distribution of the collectors on the ore minerals particles, which impacts and reduces the efficiency of the flotation process (Galed and Gallal, 2015; Vidyadhar et al., 2002). Particles in the size range of – 300 + 38 µm (in which the feldspar is naturally concentrated), were subjected to high intensity dry magnetic separation that has 18.000 Gauss (magnetic separation was carried out by an isodynamic separator Frantz instrument). The non-magnetic fraction was used as a feed for the flotation experiments. Furthermore, a flowchart was conducted and summarized the comminution, beneficiation, upgrading, and concentration processes to obtain the concentrate of feldspar (Figure 1). Figure 1 shows a flow diagram of the feldspar ore sample preparation procedure from crude ore to a finished product that relies on a wide variety of processing techniques. Different beneficiation techniques were suggested such as comminution, de-sliming, magnetic separation, and multistage of flotation. On the basis of the chemical analysis, the concentration of feldspar from the Al-Madinah area as well as the successful separation of iron and titanium oxides (the coloring materials) to enhance the purity and quality of the feldspar product could be achieved using the magnetic separation and flotation processes.

The effects of belt speed and magnetic intensity of magnetic separator on separation efficiency were examined throughout the experiments on the (-300 + 38 µm) size fraction using a laboratory magnetic separator. Other operating parameters were kept constant. The magnetic impurities ($Fe_2O_3$ + $TiO_2$ contents) were analyzed by various belt speeds, changing from 100 to 400 rpm) and using the magnetic field intensities of 3,000, 6,000, 12,000, 14,000, and 18,000 Gauss. The chemical composition of the magnetic product was presented in Table 2. The obtained non-magnetic fraction was dried and analyzed by an X-Ray fluorescence spectrometer (XRF) (Table 2). The multi-stage flotation tests were conducted using a 2-liter laboratory type Denver D12 flotation cell equipped with a 1200 rpm agitation rate. The non-magnetic concentrate was used for the flotation of micas, and heavy (iron and titanium bearing) minerals with a 200 g feed sample to remove the iron and titanium oxide minerals before flotation. The impeller speed was fixed at 1200 rpm and an aeration rate of 5 L/min was used. All experiments were performed at 24°C room temperature, using tap

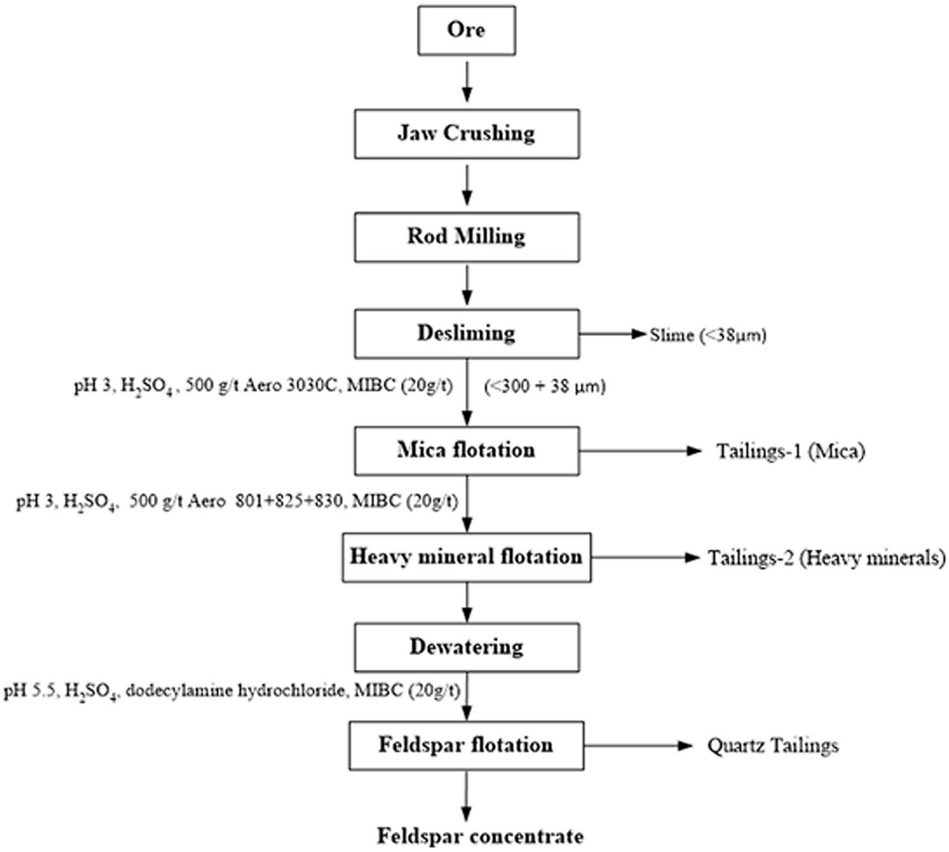


**Figure 1.** Flowsheet for beneficiation and upgrading processes of feldspar ore from Medina, Saudi Arabia

water. The total conditioning time was 6 minutes, and the solids percent are about 25 wt.%.

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. Sodium silicate ($Na_2SiO_3$) was used as a dispersant in the amount of 1000 g/t. The pH was adjusted by $H_2SO_4$ and pine oil of 20 g/t was used as a frother. The non-magnetic product was used for the following stage. In the third stage, feldspar-quartz separation was carried out. The feldspar minerals and quartz were separated from each other by flotation of feldspar minerals and depression of quartz minerals. Prior to floatation stage, many conditioning steps have been conducted to float feldspar from quartz at pH 5.5. Feldspar–quartz mixture was conditioned using oleic acid in the first step, where it adsorbed onto both minerals. However, in the second step, adsorption through aluminum resulted in its stronger adsorption on feldspar so that the addition of sodium hexametaphosphate as a dispersed agent resulted in desorption of oleate from quartz. Feldspar could then be floated from quartz with dodecylamine hydrochloride. Therefore, application of this process in this study enables to float feldspar from quartz without adding HF acid, which is more environmentally acceptable (Liu et al., 1993).

## RESULTS AND DISCUSSION

### Characterization of raw materials

The XRF results are presented in Table 1, and the $Fe_2O_3$, $TiO_2$, MgO, and CaO contents were found as 2.45 wt.%, 0.43 wt.%, 0.43 wt.%, 0.64 wt.%, respectively, as impurities. The sample has $K_2O$ and $Na_2O$ contents of 5.42 wt.% and 5.17 wt.% respectively. The XRD results (Figure 2) indicated that the feldspar ore sample was principally composed of potassium feldspar (orthoclase and microcline) and plagioclase (albite-oligoclase) followed by quartz. Small amounts of biotite and muscovite were observed.

## Magnetic separation tests

A high-intensity dry magnetic separation (18.000-Gauss) was performed to reduce the coloring iron and titanium minerals (Gougazeh, 2020; Ozdemir et al. 2011). The (-300+38) µm fraction, obtained from the comminution process, was used as feed material with different magnetic field intensity and belt speed conditions. Figures 3 and 4 show the weight of $Fe_2O_3$ + $TiO_2$ percentage variation in feed and concentrate.

Figure 3 illustrates the relationship between the different magnetic field intensities and the variation of iron and titanium contents. As shown in Figure 3, the optimum magnetic separation was produced at a field intensity of 14.000 Gauss. The obtained results from Figure 3 showed that the grade of the $Fe_2O_3$ and $TiO_2$ contents were 0.49 wt.% and 0.20 wt.% with the recovery of around 77 wt.% and 52 wt.%, respectively.

As shown in Figure 4, the contents of $Fe_2O_3$ and $TiO_2$ wt.% of the concentrates can be diminished to 0.49 wt.% and 0.20 wt.%, respectively. It can be shown that the slower belt speed of magnetic separation, gives the lower $Fe_2O_3$ and $TiO_2$ wt.% contents, positively affecting the dry magnetic separation. Figure 4 shows the $Fe_2O_3$ (78 wt.%) and $TiO_2$ (55 wt.%) removal recoveries for the feed size fraction (-300 + 38 µm) and 200 rpm belt speeds, while were 51 wt.% and 18%, respectively at a belt speed of 500 rpm. It is obvious that the removal recovery of $Fe_2O_3$ and $TiO_2$ decreases with increasing belt speed.

As clearly seen from Figures 3 and 4, it is evident that the effects of both factors (belt speed and field intensity) on magnetic separator performance, which were indicated the

**Table 1.** Chemical composition of the investigated feldspar ore sample used

| $SiO_2$ | $TiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | CaO | MnO | MgO | $Na_2O$ | $K_2O$ | $P_2O_5$ | LOI* |
|---|---|---|---|---|---|---|---|---|---|---|
| 68.64 | 0.44 | 16.50 | 2.22 | 0.45 | 0.03 | 0.40 | 4.20 | 5.01 | 0.09 | 0.70 |

* LOI – loss on ignition.

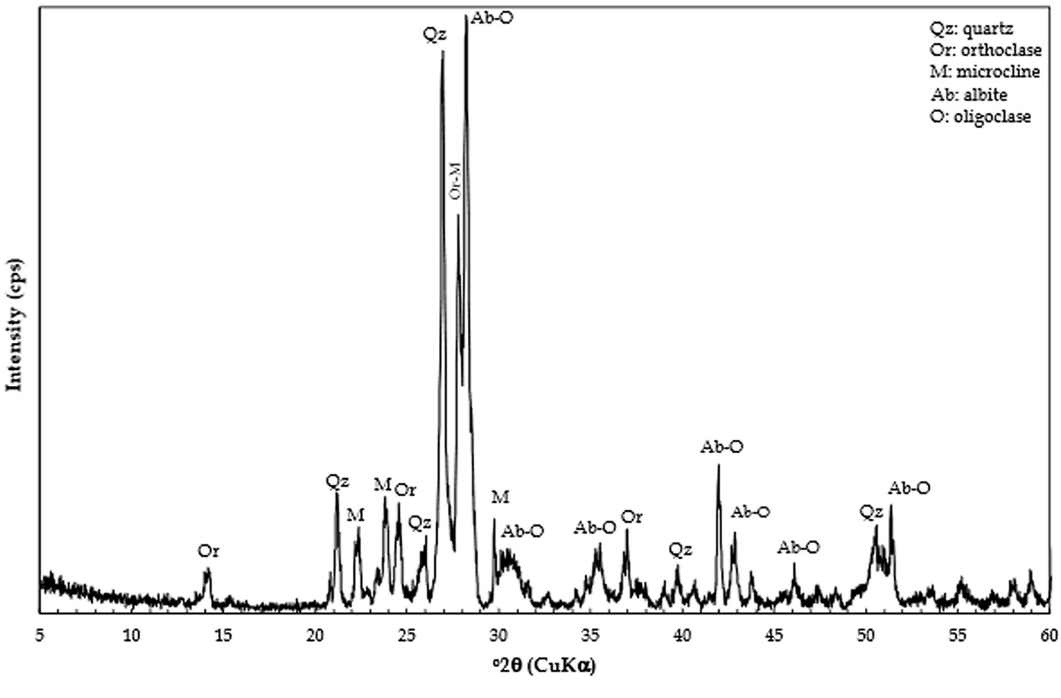


**Figure 2.** XRD pattern of the investigated feldspar ore

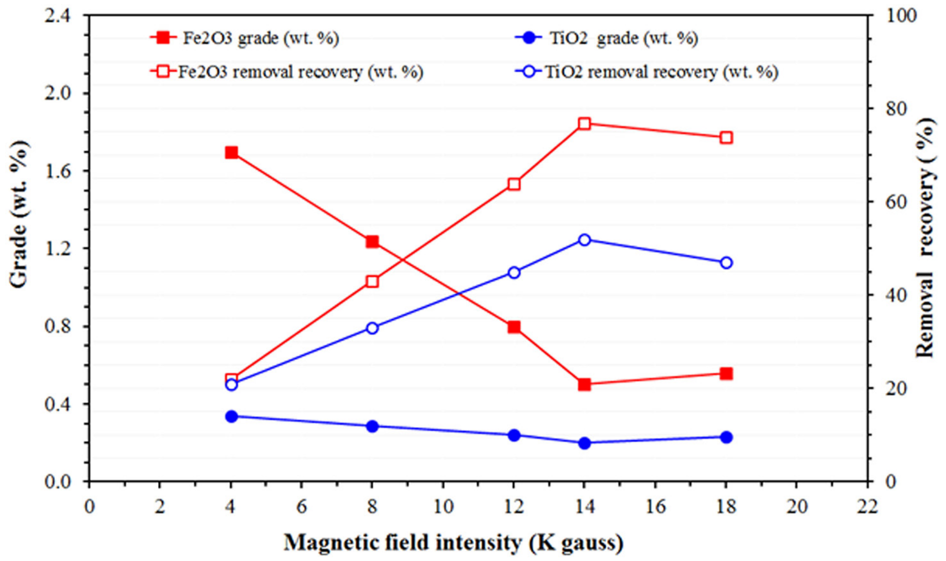


**Figure 3.** Effect of the magnetic field intensity on the performance of magnetic separator for cleaning the feed size fraction (-300 + 38 μm) of the alkali granite ore

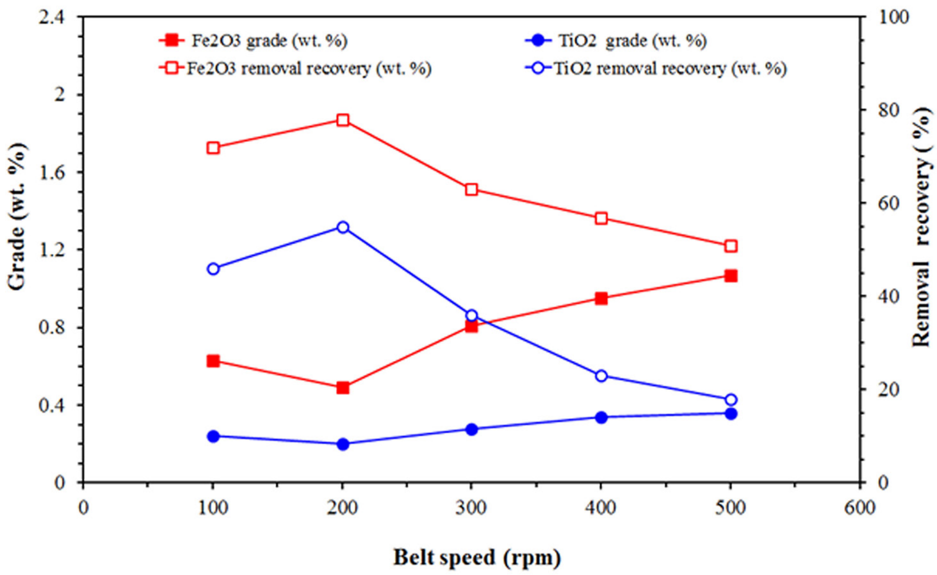


**Figure 4.** Effect of the belt speed on the performance of magnetic separator for cleaning the feed size fraction (-300 + 38 μm) of the alkali granite ore

same obtained results concerned the reduction of $Fe_2O_3$ and $TiO_2$ in the fraction feed (-300 + 38 μm fraction). The $Fe_2O_3$ and $TiO_2$ grades in the feldspar concentrate drop to 0.50 wt.% and 0.20 wt.%, respectively. Similarly, the recovery processes from removing $Fe_2O_3$ and $TiO_2$ in the feldspar concentrate were upgraded to 78 wt.% and 55 wt.%, respectively. The chemical analyses by X-ray fluorescence (XRF) of the magnetic feed fraction (-300 + 38 μm), the de-slimed fraction (-38 μm), and the magnetic products were given in Table 2.

### Flotation experiments

The flotation tests were performed on the non-magnetic fraction. This product assayed 0.50 wt.% $Fe_2O_3$, 0.20 wt.% $TiO_2$, 4.14 wt.% $Na_2O$, 5.13 wt.% $K_2O$ and 15.42 wt.% $Al_2O_3$ contains about 84% alumina in the feldspar. Feed size range of – 300 + 38 μm was used for the dry magnetic separation and the magnetic field intensity was 14,000 Gauss. In this investigation, all the discolored impurities from feldspar ore containing micaceous and heavy minerals were floated

**Table 2**. Chemical analysis of the feldspar ore feed, -300 + 38 µm, -38 µm fractions, and magnetic separation products

| Compound | Feed | -300+38 µm | -38 µm | Concentrate | Tail |
|---|---|---|---|---|---|
| Mass (wt.%) | 100 | 88.38 | 11.62 | 83.23 | 16.77 |
| $SiO_2$ | 68.64 | 70.23 | 56.64 | 70.20 | 60.12 |
| $TiO_2$ | 0.44 | 0.43 | 0.50 | 0.20 | 1.61 |
| $Al_2O_3$ | 16.50 | 16.38 | 18.04 | 15.42 | 21.18 |
| $Fe_2O_3$ | 2.22 | 2.16 | 2.65 | 0.50 | 10.41 |
| MnO | 0.03 | 0.03 | 0.04 | 0.03 | 0.05 |
| CaO | 0.45 | 0.40 | 0.86 | 0.40 | 0.40 |
| MgO | 0.40 | 0.40 | 0.41 | 0.15 | 1.62 |
| $Na_2O$ | 4.20 | 4.43 | 2.45 | 4.14 | 5.86 |
| $K_2O$ | 5.01 | 5.29 | 2.86 | 5.13 | 6.08 |
| $P_2O_5$ | 0.09 | 0.09 | 0.11 | 0.08 | 0.12 |
| LOI | 0.70 | 0.60 | 1.43 | 0.43 | 1.46 |

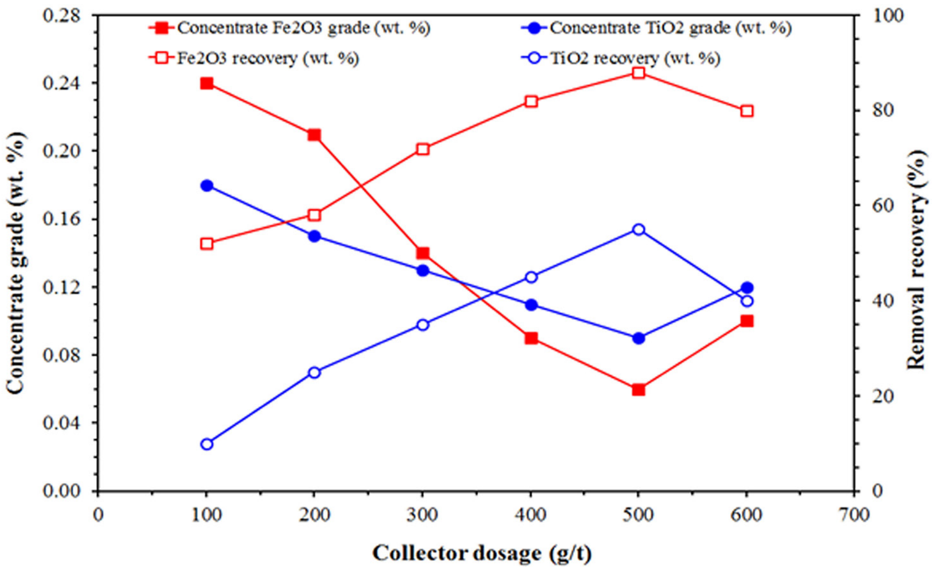


**Figure 5.** Effect of collector dosage on recovery of floated both mica and heavy minerals

with multi-stage flotation. The micaceous minerals were floated using a cationic Aero 3030C collector and a Cyanamid collector (a mixture of Aero 801, 825, and 830 promoters in a 1: 1: 1 ratio in the acidic medium at pH 3 was used as collectors for heavy mineral contents (iron- and titanium-bearing impurities). Both flotation tests were performed at the same impeller speed (1200 rpm) and percent solid by weight (25%). The results were evaluated based on the $Fe_2O_3$ % and $TiO_2$ % recoveries in the feldspar ore and the discoloring impurities ($Fe_2O_3$ and $TiO_2$) grades in the feldspar concentrate.

Figure 5 shows the relationship between the different dosage changes and the percentage variation of the iron and titanium contents which was obtained by the flotation tests. As shown in Figure 5, the contents of $Fe_2O_3$ and $TiO_2$ decreased, and the removal recovery increased along with froth, as the reagent dosage increased. Furthermore, the removal recovery rate increased from 52 wt.% to 79 wt.% and from 77 wt.% to 97 wt.% for $Fe_2O_3$ and $TiO_2$, respectively, with the collector dosage up to 500 g/t. The best flotation results were obtained at 500 g/t dosage which produced a high-grade feldspar concentrate with 0.06 wt.% $Fe_2O_3$ and 0.09 wt.% $TiO_2$ contents in an acidic medium at pH 3. The typical specifications of commercial feldspar assaying: the alkaline content $Na_2O$ + $K_2O$ is about 11–13 wt.%, < 1.5 wt.% of CaO and MgO, the total content of $Fe_2O_3$ and $TiO_2$ ranges from 0.07 to 0.3 wt.% and the content of free silica range from 8 to 10 wt.% (Karagüzel and Cobanoglu, 2010). Accordingly, as can be seen from obtained results, the specifications of the produced feldspar concentrate in the present study fulfilled the glass and ceramics production requirements.

## CONCLUSIONS

High grade feldspar products with a high alkaline ratio and low Fe- and Ti- contents were produced. The following findings were confirmed. On the basis of the chemical analysis, the iron and titanium oxides contained in the feldspar ore are 2.22 wt.% and 0.44 wt.% which are still considered high for manufacturing whiteware ceramics. However, if the feldspar ore is to be used for the manufacturing of white ceramics, then this Madinah feldspar still needs to be beneficiated by reducing the total of iron and titanium contents to below 1.0 wt.%. A magnetic separator is applied individually with a magnetic field intensity of 14.000 gauss. After the magnetic beneficiation process, the contents of $Fe_2O_3$ and $TiO_2$ were reduced to 0.5 wt.% with 77 wt.% recovery and to 0.2 wt.% with 52 wt.% recovery, respectively. This is in accordance with the specifications of the glass and ceramic (porcelain) industries. The non-magnetic concentrate was obtained by magnetic separation process assaying 5·13 wt.% $K_2O$ and 4·14 wt.% $Na_2O$. However, 83 wt.% of the produced medium-grade feldspar can be upgraded by flotation process to meet the specifications for both ceramic and glass industry. In this study, the discolored impurities in feldspar ore, which do not allow its marketing, were successfully removed through a combination of magnetic separation and single-stage flotation. The obtained results indicated high quality and a marketable feldspar concentrate with 0.06 wt.% $Fe_2O_3$ and 0.09 wt.% $TiO_2$ grades were produced at 500 g/ton dosage of effective blends of collectors (Aero 801 + 825 + 830 promoters) in an acidic medium at pH 3 by a single-stage flotation. Mica and heavy (iron and titanium bearing) minerals were removed from the ore by the performed magnetic separation and single-stage flotation processes, with recoveries of 97 wt.% $Fe_2O_3$ and 79 wt.% $TiO_2$. The feldspar concentrate assaying 0.06 wt.% $Fe_2O_3$, 0.09 wt.% $TiO_2$, 9.09 wt.% $K_2O$, 6.01 wt.% $Na_2O$, and 19.02 wt.% $Al_2O_3$ was obtained with a high alkaline content (> 15 wt.% $K_2O + Na_2O$). It is remarkable that the obtained high-quality feldspar can be used for glass and ceramics productions. These results exhibited the best performance of beneficiation processes and positive environmental impacts.


### Acknowledgments

The Financial and technical supports for this work was provided by Tafila Technical University (TTU), Jordan, and the German Research Foundation ‘‘Deutsche Forschungsgemeinschaft’’ (DFG), Germany are gratefully acknowledged. The author wishes to express his thanks to the Institutes of Mineralogy and inorganic chemistry, Leibniz University, Hannover, Germany that allowed the use of their research laboratories.


## REFERENCES


1. Deer W.A., Howie R.A., Zussman J. 2001. Rock-forming Minerals (2nd edition). Geological Society of London, London, 4A.
2. Galed M.E., Gallal W. 2015. Beneficiation of feldspar ore for application in the ceramic industry: Influence of composition on the physical characteristics. Arabian Journal of Chemistry, 8(2), 186–190.
3. Gougazeh M., Bamousa A., Hasan A. 2018. Evaluation of granitic rocks as feldspar source: Al Madinah, western part of Saudi Arabia. Journal of Taibah University for Science, 12(1), 21–36.
4. Gougazeh M. 2020. Beneficiation study of low-grade Jordanian kaolin to increase the brightness index. Jordan Journal of Civil Engineering, 14(3), 319–330.
5. Heyes G.W., Allan G.C., Bruckard W.J., Sparrow G.J. 2012. Review of flotation of feldspar. Mineral Processing and Extractive Metallurgy, 121, 72–78. http://dx.doi.org/10.1179/1743285512Y.0000000004
6. Liu Y., Gong H., Qui J., Zhang K. 1993. A new flotation technique for feldspar-quartz separation, Proc. XVIII Int. Mineral Processing Cong., Sydney, NSW, Australia, May, The Australasian Institute of Mining and Metallurgy, 4, 857–862.
7. Karaguzel C., Cobanoglu G. 2010. Stage-wise flotation for the removal of colored minerals from feldspathic slimes using laboratory scale Jameson cell. Separation and Purification Technology, 74(1), 100–107.
8. Neuendorf K.K.E., Mehl J.P., Jr., Jackson J.A. 2011. Glossary of Geology. American Geological Institute, Alexandria, Virginia, 799.
9. Ozdemir O., Gupta V., Çinar M., Çelik M., Miller J. 2011. Production of trona concentrates using high intensity dry magnetic separation followed by flotation. Minerals and Metallurgical Processing, 28(2), 55–61.
10. Vidyadhar A., Hanumanth Rao K., For Mossberg K.S.E. 2002. Separation of feldspar from quartz: mechanism of mixed cationic/anionic collector adsorption on minerals and flotation selectivity. Minerals and Metallurgical Processing, 19(3), 128–136.