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### REMOVING IRON IMPURITIES FROM FELDSPAR ORE USING DRY MAGNETIC SEPARATION (PART ONE)

Feldspar is a basic requirement for glass, ceramics, and other industries. The presence of iron in feldspar is one of the challenging aspects of feldspar processing. To improve the quality of feldspar for use in various industries, dry magnetic separation is one of the best techniques for reducing iron in feldspar, especially in arid regions to overcome the common problem of lack of water resources as well as to reduce the operational cost of the enrichment process. Therefore, dry magnetic separation experiments were carried out to remove the iron content from feldspar ore in the Wadi Umm Harjal area in Egypt to meet the specifications required for different industries. The sample was analysed using XRD, XRF, and optical microscopy, which revealed that it is a mixture of potassium feldspar (microcline/orthoclase), albite, and quartz in the presence of hematite mineral serving as the main iron impurities in addition to the free silica content. The effect of parameters on the activity of the dry high magnetic separators was investigated in addition to cleaning the products. The iron oxide reduced from 0.69% in the head sample to 0.08% after dry high-intensity magnetic separation, and the whiteness increased from 82.01% in the head sample to 95.97% in the separated concentrate. The experimental results showed that there is a possibility to obtain feldspar concentrates with low content of  $\text{Fe}_2\text{O}_3$  from the area where according to the results, approximately 88.4% of iron was removed from the head sample.

**Keywords:** feldspar; magnetic separation; iron impurities; hematite; Wadi Umm Harjal

## 1. Introduction

Industrial mineral raw materials are essential for economic development. Reliable supplies of good quality construction materials and a wide range of other industrial mineral raw materials

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are necessary for infrastructure improvement and growth of the manufacturing sector. With the expansion of industry, the desire for feldspar ore is increasing. Due to its properties, feldspar is extensively used in several industrial fields [1]. As a major component in the glass industry, feldspar is also used as a raw material in the manufacture of ceramic articles, paints, rubber latex, fiberglass, fertilizer, and other products [2-5].

In Egypt, high-quality sodium feldspar (Na-feldspar) is produced from South Sinai, whereas potassium feldspar (K-feldspar) is produced from the pegmatites and granitic rocks of the various wadies in the Eastern Desert. Compared to the Eastern Desert's feldspars, which are tainted with free quartz and iron oxides, Sinai feldspars are of higher quality [6]. Significant reserves of feldspar varieties are in the Eastern Desert of Egypt, and the majority are utilised without treatment [7].

The feldspars are considered the majority of the predominant minerals, estimated to make up nearly 60% of the earth's crust [8,9]. Largely, feldspar is used in glass-making products (70%), while in ceramics and other products (30%) [10]. Feldspar is applied in glass manufacturing as a fluxing factor as well as a source of alkali ( $K_2O$  &  $Na_2O$ ), alumina ( $Al_2O_3$ ), and silica [11-13]. The standard specifications of the marketed feldspar require  $SiO_2 < 70\%$ ,  $Al_2O_3 > 17\%$ ,  $Fe_2O_3 < 0.1\%$  with  $K_2O$  and  $Na_2O$  both  $> 5\%$  [14].

The attendance of colouring constituents, mainly iron oxide in feldspar ore, led to losses in its quality because of making a black spot in the product build through the firing procedure as well as adding colour to the finished product [15-18], as a result, iron quantity in glass and ceramics must be maintained below a specific level, 0.10% for glass and 0.07-0.08% for ceramics [19-21]. A magnetic separation technique is required for feldspar purification since non-magnetic feldspar accompanies some worthless magnetic minerals such as rutile, hematite, pyrite, tourmaline, and white mica [22-25]. In general, the gangue minerals in feldspar appear to have weak magnetic characteristics; just using a high-intensity magnetic separator can get a good result [23,26]. Most often, ferromagnetic materials such as magnetite are separated using dry or wet low-intensity magnetic separators, while paramagnetic minerals such as hematite are separated using high-intensity magnetic separators [27,28]. Due to their low cost, high-intensity dry magnetic separators are becoming increasingly popular for the separation of paramagnetic materials [29]. The separation effectiveness of these separators is determined by mineral properties, equipment design features, and process variable optimization [30,31]. Given the low specific magnetic susceptibility of hematite (range from  $10 \times 10^{-8} \text{ m}^3/\text{kg}$  to  $760 \times 10^{-8} \text{ m}^3/\text{kg}$ ), it should be enriched at high values of magnetic intensity ranging from 0.02-4.0 Tesla [32,33].

Many researchers use flotation processes when separating iron or mica from feldspar and other minerals, and this is expensive due to the high prices of reagents in addition to the harmful effects of some of them on the environment [34-38].

This study aims to separate the iron oxide from Wadi Umm Harjal feldspar ore by the potential of dry enrichment to overcome the common problem of lack of water resources, as well as to reduce the operational cost of the beneficiation process. The recovery was successfully performed using a dry high-intensity magnetic separator in the coarse size range for reducing the grinding process volume and energy consumption.

## 2. Materials and methods

The representative feldspar sample was obtained from the Wadi Umm Harjal area, about 85 km southwest of the Marsa Alam town on the Red Sea coast, Egypt. The ore preparation process

of feldspar ore to prepare as feed for the concentration process involves crushing, grinding by ball mill, and using attrition scrubbing.

## 2.1. Crushing and grinding of feldspar ore

The run of mine feldspar sample was crushed to  $-8$  mm in a laboratory ( $5'' \times 6''$ ) Denver jaw crusher. The  $-8$  mm sample was crushed to  $-4$  mm in a small laboratory ( $2.25'' \times 3.5''$ ) Denver jaw crusher. The  $-4$  mm sample was crushed to  $-1$  mm using a laboratory ( $6'' \times 10''$ ) Denver roll crusher in a closed circuit with a  $1$  mm sieve. The roll crusher product was ground to  $-0.25$  mm using a ball mill (Bico Braun laboratory ball mill MFD, By Bico INC Burbank Calif) in a closed circuit with a  $0.25$  mm sieve. The crushed products after the jaw crusher and roller crusher were thoroughly mixed and divided into representative samples ( $5$  kg each) using coning and quartering technique. A representative sample of about two kilograms was taken for size analysis, and a sample of about  $50$  g from a size less than  $2$  mm was employed for characterisation after finely ground using a laboratory ball mill. The slimes ( $-0.053$  mm) were separated by wet screening. The attrition process was executed for the fraction ( $0.053$ - $0.25$ ) mm in an attrition machine. The attrition process was implemented at solids percentage of  $60\%$  at  $1700$  rpm of impeller speed for  $15$  minutes. The attrition product was screened on  $0.053$  mm, as shown in Fig. 1. The fraction ( $0.053$ - $0.25$ ) mm was used in the magnetic separation experiments before and after the attrition process.

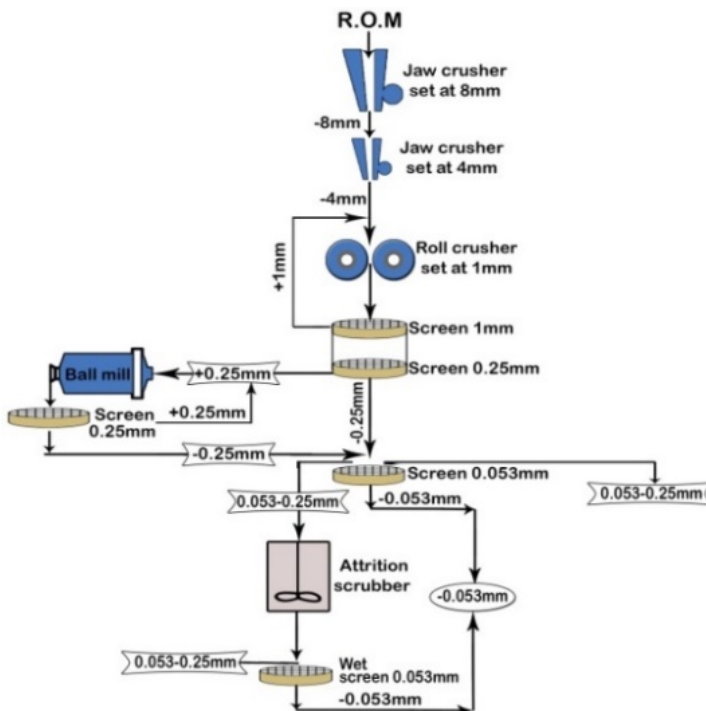


Fig. 1. Flowsheet of crushing, grinding & attrition procedure

## 2.2. Dry high intensity magnetic separators

Two types of magnetic separators were used in the experimental study.

### 2.2.1. Rare earth roll magnetic separator “Magna Roll”

The Magna Roll separator is a rolling type of work that operates on a dry basis with fixed magnets with high field intensity equal to 2T. The roll-type magnets (permanent magnetic roll) are formed of alloys of rare earth magnetic elements and are utilised in the roller magnetic separators. These rolls are more powerful than ordinary magnetic magnets (Fig. 2). Due to their magnetic characteristics and unique magnetic series, they produce strong magnetic attraction forces on the magnetic roller. This strong magnetic force can separate minerals with weak magnetic properties because the obtained high magnetic attraction forces have low magnetic sensitivity.

### 2.2.2. Induced roll magnetic separator “Carpco”

The laboratory “Carpco” dry high-intensity magnetic separator (Lift-Type Induced Roll, Model MLH-13-111-5) was used in this study, as shown in Fig. 3. Its processing capacity of granular material up to 90 kg/h and has a variable magnetic field intensity of up to 1.96T, and 127 mm diameter × 50.8 mm length laminated roll with changeable speed from 0-100 rpm. It is intended to separate components that are moderately or weakly magnetic (paramagnetic) from non-magnetic components.



Fig. 2. The magna roll separator



Fig. 3. Carpco magnetic separator

## 3. Results and discussion

### 3.1. Sample characterisation

A complete chemical analysis of the head sample was carried out using X-Ray Fluorescence (XRF) technique; the results are shown in Table 1. The results showed that the feldspar sample is of low grade under market standards for the manufacturing of glass and ceramic/pottery grade

feldspar specifications [14,19]. Iron oxide contents (0.69%) should be reduced to <0.1% to be suitable for different industries. According to X-Ray Diffraction (XRD) analysis, the sample is composed mainly of alkali feldspar (microcline/orthoclase), quartz, and plagioclase (Albite), as shown in Fig. 4 and Table 2. From optical microscopy, the rock is medium to very coarse-grained, showing granular, hypidiomorphic, well-developed perthitic (intergrowth of plagioclase and alkali feldspar), micrographic, and poikilitic textures. Some micro-fractures are observed cutting through the rock. In addition to the main components of the sample, there are rare amounts of mica (biotite and muscovite) with accessory opaque minerals. Secondary minerals are represented by clay minerals, sericite, carbonates, chlorite, and iron oxides. Alkali feldspars occur as a medium to very coarse-grained, generally subhedral to anhedral crystals and slightly to partially altered to clay minerals. Figs 5-8 show all minerals in the head sample through the thin section under a microscope with zoom (25X, C.N.).

TABLE 1

Chemical composition of the head sample using XRF technology

Component	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Na <sub>2</sub> O	K <sub>2</sub> O	Fe <sub>2</sub> O <sub>3</sub>	CaO	MgO	MnO	TiO <sub>2</sub>	P <sub>2</sub> O <sub>5</sub>	LOI
Content%	72.38	16.13	2.83	5.55	0.69	1.32	0.07	0.06	0.06	0.05	0.7

TABLE 2

Mineralogical composition of the sample from XRD analysis

Mineral Name	Chemical Formula	Semi-Quant [%]
Microcline	K [Al Si <sub>3</sub> O <sub>8</sub> ]	40
Orthoclase	K [Al Si <sub>3</sub> O <sub>8</sub> ]	15
Albite	Na [Al Si <sub>3</sub> O <sub>8</sub> ]	25
Quartz	SiO <sub>2</sub>	20

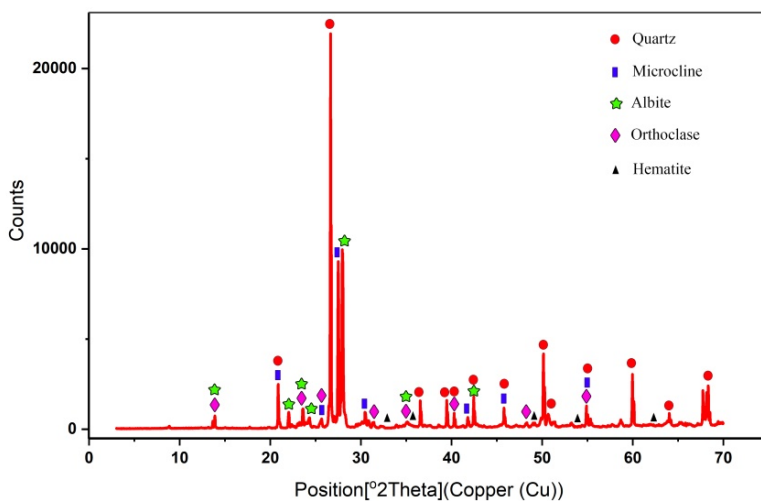


Fig. 4. The XRD chart of head sample

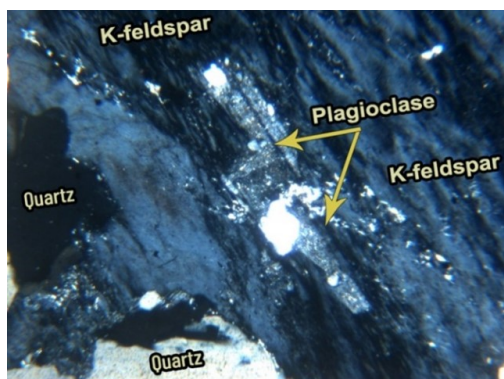


Fig. 5. Photomicrograph showing plagioclase (albite) intergrown with perthite K-rich pegmatite

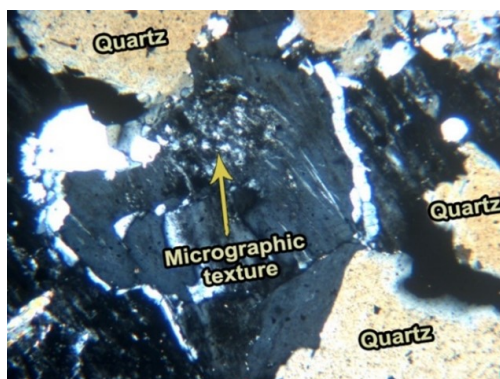


Fig. 6. Photomicrograph showing quartz surrounds micrographic texture of k-feldspar

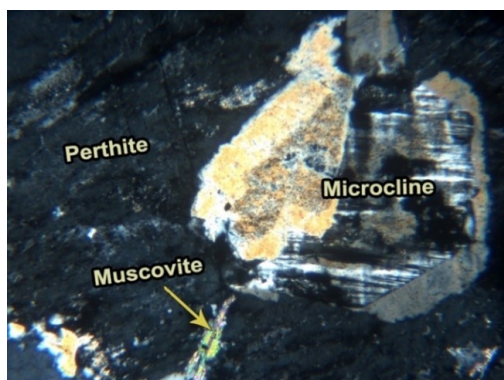


Fig. 7. Photomicrograph showing microcline crystals show distinct lamellar twinning and intergrowths with perthite in the K-rich pegmatite

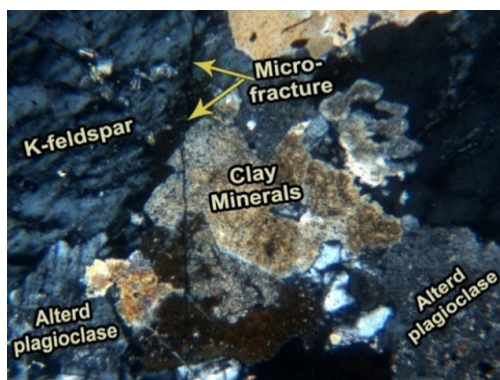


Fig. 8. Photomicrograph showing K-feldspar altered to clay minerals, plagioclase altered to sericite and carbonates & mica altered to chlorite and iron oxides

### 3.2. Magnetic separation process (without attrition scrubbing)

The “Magna Roll” separator and the “Carpco” magnetic separator were tested, as was previously described. The feldspar sample was ground to different sizes (–2 mm, –0.5 mm, –0.25 mm, and –0.125 mm). Then, the fine fraction below –0.045 mm was separated with a 0.045 mm wet sieve before conducting the magnetic separation experiments. The following Tables 3, 4, 5, and 6 represent the chemical analysis of the different fractions (0.045–2) mm, (0.045–0.5) mm, (0.045–0.25) mm, and (0.045–0.125) mm, respectively.

#### 3.2.1. Results of the magna roll separator

The results from Fig. 9 clearly showed that the “Magna Roll” did not separate the iron oxide impurities from size (0.045–2) mm. However, when the size of the feed sample was reduced to

TABLE 3

Chemical analysis of (0.045-2) mm size

Size, mm	Wt.%	SiO <sub>2</sub> %	Al <sub>2</sub> O <sub>3</sub> %	Na <sub>2</sub> O%	K <sub>2</sub> O%	Fe <sub>2</sub> O <sub>3</sub> %	CaO%
0.045-2	96.30	72.73	16.43	3.02	5.23	0.66	1.29
-0.045	3.70	63.27	8.32	2.11	13.87	1.47	7.77
Assay%	100.00	72.38	16.13	2.83	5.55	0.69	1.32

TABLE 4

Chemical analysis of (0.045-0.5) mm size

Size, mm	Wt.%	SiO <sub>2</sub> %	Al <sub>2</sub> O <sub>3</sub> %	Na <sub>2</sub> O%	K <sub>2</sub> O%	Fe <sub>2</sub> O <sub>3</sub> %	CaO%
0.045-0.5	80.51	72.87	16.34	2.67	5.34	0.65	1.44
-0.045	19.49	72.18	15.31	2.77	6.06	0.95	0.92
Assay%	100.00	72.73	16.13	2.68	5.55	0.71	1.32

TABLE 5

Chemical analysis of (0.045-0.25) mm size

Size, mm	Wt%	SiO <sub>2</sub> %	Al <sub>2</sub> O <sub>3</sub> %	Na <sub>2</sub> O%	K <sub>2</sub> O%	Fe <sub>2</sub> O <sub>3</sub> %	CaO%
0.045-0.25	89.85	71.81	17.52	2.95	5.38	0.67	1.39
-0.045	10.15	77.43	3.82	1.77	1.5	1.01	0.70
Assay%	100.00	72.38	16.13	2.83	5.55	0.70	1.32

TABLE 6

Chemical analysis of (0.045-0.125) mm size

Size, mm	Wt%	SiO <sub>2</sub> %	Al <sub>2</sub> O <sub>3</sub> %	Na <sub>2</sub> O%	K <sub>2</sub> O%	Fe <sub>2</sub> O <sub>3</sub> %	CaO%
0.045-0.125	85.15	71.89	17.32	2.84	5.46	0.70	1.39
-0.045	14.85	75.18	9.31	2.77	6.06	0.80	0.92
Assay%	100.00	72.38	16.13	2.83	5.55	0.71	1.32

(0.045-0.25) mm and (0.045-0.125) mm, the results were improved. The iron oxide was decreased to ~0.25% Fe<sub>2</sub>O<sub>3</sub> (error ±0.012%). From these results, the feed sample (0.045-2) mm needs further grinding to reach an appropriate degree of liberation between feldspar contents and iron oxide.

### 3.2.2. Results of the carpc magnetic separator

Three experimental tests were carried out on the three different sizes of feldspar (0.045-0.5) mm, (0.045-0.25) mm, and (0.045-0.125) mm, and were used as feed at maximum working conditions. The results are illustrated in Fig. 10.

The results obtained from the “Carpco” magnetic separator indicated that the dry magnetic separation method can be successfully applied in feldspar enrichment. From the results, the weight percent of non-magnetic products from the “Carpco” magnetic separator is high compared with those from the Magna Roll.

The results also showed that there is no critical impact on the separation weight recovery from the three diverse size fractions, also the percentage of Fe<sub>2</sub>O<sub>3</sub> reduced from 0.69% in the

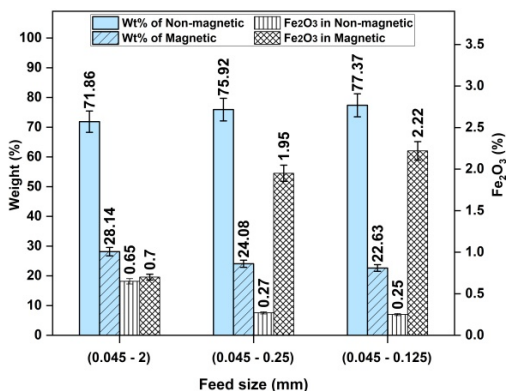


Fig. 9. The results of the magna roll separator for different size fractions of the sample

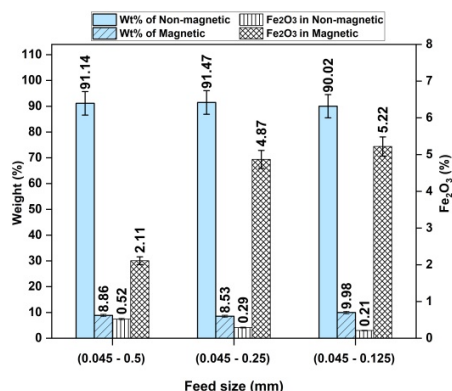


Fig. 10. The results of the "Carpco" magnetic separator for different size fractions of the sample

feed sample to 0.52% (error  $\pm 0.026\%$ ) in (0.045-0.5) mm fraction, to 0.29% (error  $\pm 0.014\%$ ) from 0.67% in (0.045-0.25) mm, and to 0.21% (error  $\pm 0.010\%$ ) from 0.70% in (0.045-0.125) mm fraction.

Reducing the iron oxide to these values encouraged us to study different parameters that affect the "Carpco" magnetic separator after changing the particle size to 0.053 mm in two cases to increase separation efficiency and used as a feed for cationic flotation (part two). Therefore, a feed sample of (0.053-0.25) mm was prepared for magnetic separation experiments without attrition scrubbing (A) and after attrition scrubbing (B) to show the effect of slimes on the separation operation.

### (A) Magnetic separation of (0.053-0.25) mm without attrition scrubbing

Table 7 shows the chemical analysis of the feed sample for the magnetic separation experiments. The iron oxide was reduced from 0.69% to 0.51% by comminution processes and desliming the -0.053 mm by dry method. Hence, the desliming method removed approximately 26.09% of the total iron content into a fraction of -0.053 mm.

TABLE 7

The XRF analysis of (0.053-0.25) mm size

Component	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Na <sub>2</sub> O	K <sub>2</sub> O	Fe <sub>2</sub> O <sub>3</sub>	CaO
%	72.44	15.43	2.45	5.98	0.51	1.30

Fig. 11 shows the results of magnetic separation using a Magna Roll separator at a feed rate of 3.5 gm/min and maximum field intensity of 2T with different values of angle and speed.

Iron oxide was reduced to 0.18% (error  $\pm 0.009\%$ ) from 0.51% at an angle of 90° and speed of 18.7 rpm with a 95.3% non-magnetic yield. When the angle was changed to 95° and the speed to 20.18 rpm, the weight% of non-magnetic became 97.41% and the iron oxide reduced to 0.17 (error  $\pm 0.026\%$ ), as shown in Fig. 11. The fraction (0.053-0.25) mm was also separated by a "Carpco" magnetic separator at a feed rate of 3.5 g/min., roll speed of 100 rpm, angle of 90° with



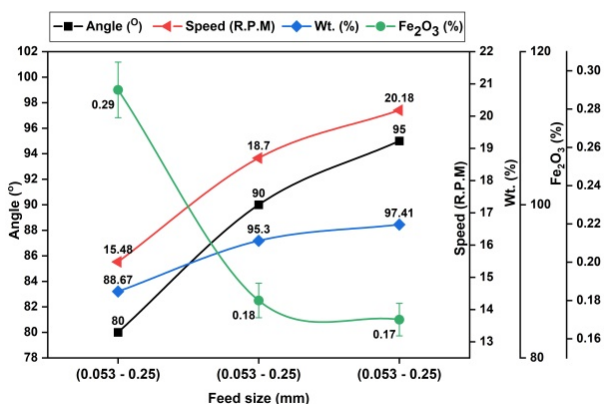


Fig. 11. The results of magna roll without attrition scrubbing at (0.053-0.25) mm size

a maximum current intensity at 3.4 amperes, magnetic field intensity at 1.96T and then the product was cleaned twice. The iron oxide was reduced to 0.12% (error  $\pm 0.006\%$ ), as shown in Fig. 12.

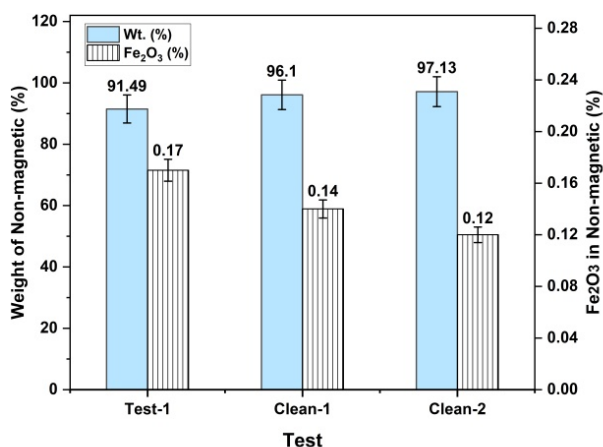


Fig. 12. The results of the carpc magnetic separator of (0.053-0.25) mm after cleaning twice

This non-magnetic product can be used in porcelain and some types of ceramics after decreasing the silica and raising the content of (Na<sub>2</sub>O + K<sub>2</sub>O) as well as alumina content by cationic flotation (part two). At the same time, the results of magnetic separation can be improved after applying the attrition scrubbing process for (0.053-0.25) mm size fraction.

### (B) Attrition scrubbing for the (0.053-0.25) mm & use dry magnetic separation

Table 8 shows the chemical analysis of the sample where the iron oxide was reduced to 0.39% from 0.51% after attrition scrubbing for 15 minutes with 60% solid/liquid at 1700 rpm

of impeller speed, and 23.53% of the  $\text{Fe}_2\text{O}_3$  content was reduced. This indicates that grinding with attrition scrubbing was better than without attrition scrubbing.

TABLE 8

The results after attrition scrubbing for (0.053-0.25) mm

Size, mm	Wt.%	$\text{SiO}_2\%$	$\text{Al}_2\text{O}_3\%$	$\text{Na}_2\text{O}\%$	$\text{K}_2\text{O}\%$	$\text{Fe}_2\text{O}_3\%$	$\text{CaO}\%$
0.053-0.25	91.42	75.23	14.35	2.89	5.55	0.39	1.45
-0.053	8.58	64.63	22.47	3.65	4.14	1.81	1.27
Assay%	100	74.32	15.05	2.95	5.43	0.51	1.43

Applying magnetic separation for this sample using a Magna Roll separator and a Carpcio magnetic separator under optimum conditions decreased the iron oxide to 0.082% and 0.08% (error  $\pm 0.004\%$ ), respectively, after cleaning twice, as shown in Figs. 13 & 14. In addition, it was observed that the Carpcio magnetic separator have a higher mass recovery from the concentrated product than the Magna Roll separator in this type of feldspar.

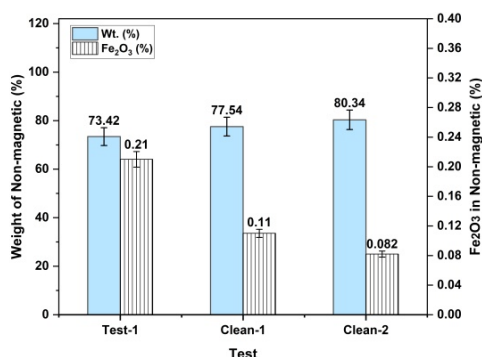


Fig. 13. The results of magna roll separator of (0.053-0.25) mm after attrition scrubbing and cleaning twice

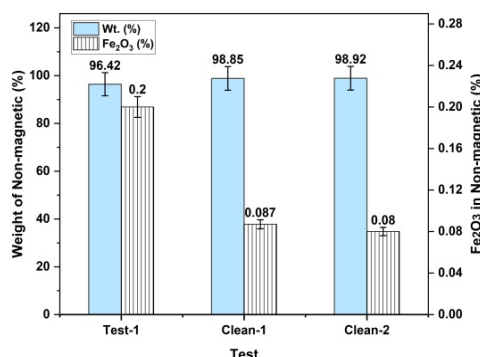


Fig. 14. The results of Carpcio magnetic separator of (0.053-0.25) mm after attrition scrubbing with twice cleaning

From these results of dry magnetic separation after attrition scrubbing and cleaning twice, the iron oxide was reduced to 0.08%, which is a great achievement from a scientific and technical point of view. The proposed flow sheet for iron oxide removal by dry high-intensity magnetic separation is shown in Fig. 15.

### 3.3. Characterisation of the final product

XRD analysis was conducted for the feed sample before and after magnetic separation. It was found that most of the hematite bands regressed and disappeared in the product after magnetic separation. In some bands, the hematite peaks became smoother, as shown in Fig. 16 & Fig. 17.

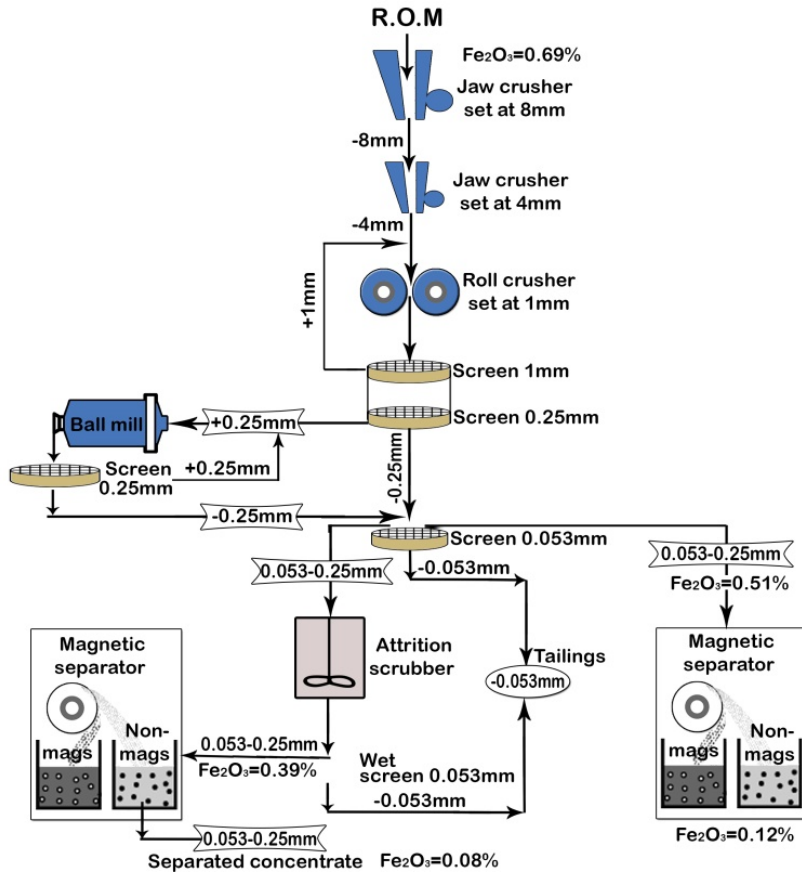


Fig. 15. Suggested Flow sheet of removing iron oxide using dry magnetic separation

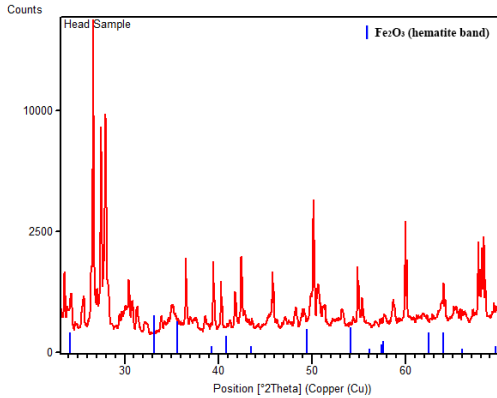


Fig. 16. The XRD analysis shows the hematite bands before magnetic separation

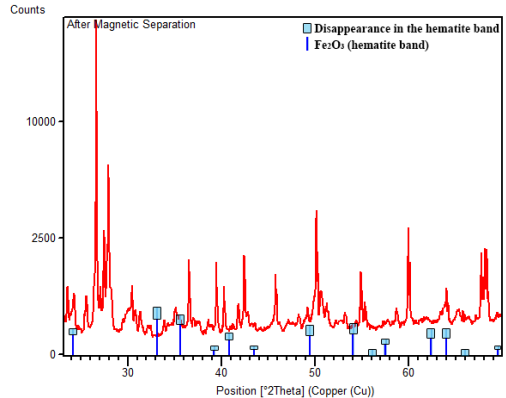


Fig. 17. The XRD analysis shows the disappearances in hematite bands after magnetic separation processes

TABLE 9

The properties of sample before and after attrition scrubbing for (0.053-0.25) mm

Property%	Iso-Brightness	Brightness	Whiteness	Redness	Yellowness
Origin sample%	67.25	55.37	82.01	3.82	9.77
After reducing iron oxide%	92.10	89.88	95.97	0.11	1.61



Fig. 18. Photograph showing the difference in whiteness before and after magnetic separation

Table 9 and Fig. 18 show the whiteness improved from 82.01% in the original sample to 95.97% in the separated non-magnetic product. Increasing whiteness was related to attrition scrubbing and dry magnetic separation.

## 4. Conclusion

In order to reduce the iron content in the feldspar sample in the Wadi Umm Harjal region to be suitable for use in industry, dry high-intensity magnetic separation experiments were conducted. The results were as follows:

- From the technical point of view, dry magnetic separators will be effective for feed sample finer than 0.25 mm and more than 0.053 mm.
- Comminution and desliming operations reduced the content of  $\text{Fe}_2\text{O}_3$  from 0.69 % in the head sample to 0.51% in the (0.053-0.25) mm fraction, with a mass recovery of 80.64%, i.e., 26.09 % of the iron was removed.
- The optimum condition was obtained at a feed rate of 3.5 g/min., field intensity of 2T, angle of  $90^\circ$  and speed of 18.7 rpm without attrition scrubbing as the iron oxide was decreased to 0.18% with 95.3% of non-magnetic yield using a Magna Roll separator. At the same time, the optimum condition using a Carpc separator was obtained at a feed rate of 3.5 g/min., roll speed of 100 rpm, angle of  $90^\circ$  with maximum field intensity at 1.96T as well as cleaning the product twice as the iron oxide was decreased to 0.12% with 97.13% of non-magnetic yield.

- Applying attrition scrubbing process for the size fraction (0.053-0.25) mm reduced the iron oxide from 0.51% to 0.39%, i.e., 23.53% of  $\text{Fe}_2\text{O}_3$  was removed at solid/liquid 60%, 1700 rpm, and conditioning time 15 min.
- In the optimal condition of each separator with cleaning the product twice, applying dry magnetic separation for the sample (0.053-0.25) mm after attrition scrubbing by Magna Roll and Carpc magnetic separators, the iron oxide decreased to 0.082% and 0.080 with a wt. % yield of 80.34% and 98.92%, respectively.
- The total iron eliminated into the  $-0.053$  mm fraction (slimes) constituted about 88.4% of the total iron found in the original sample.
- The iron oxide was reduced to the desired value by using dry magnetic separators in the coarse fraction without the need for further grinding.
- Regression, as well as the disappearance of iron peaks (hematite) in the XRD chart of the final product after magnetic separation, indicated that the dry magnetic separation is an effective method for removing iron oxide from the feldspar ore.
- Increasing the whiteness of the final product indicated that the dry magnetic separation is highly effective in reducing iron oxide.
- After reducing the iron content in the sample to the acceptable limit in different industries, the sample needs to increase the percentage of alkali along with reducing the percentage of free silica and this will be discussed in future work (Part Two).

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