ENRICHMENT OF AYDIN FELDSPARS CONTAINING MAFIC MINERALS THROUGH AN OPTICAL SORTING METHOD

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ABSTRACT

Western Anatolian (Türkiye) feldspars, one of the important mineral resources of the ceramics and glass industry, are commonly found together with mafic minerals. However, the presence of mafic minerals negatively affects the quality and market value of the feldspar concentrate and causes problems in ceramic production. In this study, we propose an innovative approach for the enrichment of Aydın feldspars (Western Anatolia), utilizing an optical sorting method to effectively separate feldspar from mafic minerals based on their different optical properties. The research methodology involved a series of laboratory-scale experiments, including mineralogical and chemical analyses, optical sorting tests, and characterization of the processed products. Initially, the Aydın feldspar samples were subjected to comprehensive mineralogical and chemical investigations to determine their composition and identify the associated mafic minerals. The results revealed the presence of minerals such as hematite, tourmaline, and muscovite, which contribute to the reduction of feldspar quality.

To overcome this difficulty, an optical classification system was used to separate feldspar grains from associated mafic minerals. Separation tests were carried out by optimizing various parameters of the feed size to achieve maximum efficiency. The separated products were further analyzed to evaluate the effectiveness of the separation process (XRF, XRD and firing properties). The findings of this study demonstrated that the optical sorting method effectively enhanced the feldspar concentrate by selectively removing the mafic minerals. The processed feldspar samples exhibited improved quality, with reduced concentrations of detrimental minerals. The optimization of the sorting parameters led to enhanced separation efficiency, with a considerable increase in feldspar recovery and purity. The proposed approach for the enrichment of Aydın feldspars through optical sorting provides a promising solution for the mining industry, enabling efficient utilization of mineral resources and improving the economic viability of feldspar deposits. Furthermore, the successful implementation of this method contributes to sustainable mineral processing practices by reducing waste generation and environmental impacts associated with conventional beneficiation techniques.

INTRODUCTION

Western Anatolia in Türkiye ranks first in Europe in terms of Na-feldspar potential and production. In 2022, about 8 million tons of Na-feldspar was exported and there is a domestic consumption of 2.5 million tons. Therefore, Western Anatolia has an annual production of 10 million tons of feldspar [1]. For this reason, Western Anatolian Na-feldspar resources are being rapidly consumed day by day and there is no alternative natural raw material to replace them. This situation has brought to the agenda the use of feldspathic rocks containing less than 7% Na_2O, which is defined as poor/low quality today.

In order to utilize natural raw material resources with low Na_2O content, a series of mineral beneficiation processes are required. The best known and most widely used of these is the flotation method. Another is optical sorting. Sometimes these two methods are used in combination. The optical beneficiation method has been widely used in recent years, especially in the food industry for grain sizing and separation of foreign materials, such as rock fragments, from grains.

The main parameter used in optical enrichment is the optical properties, such as color, brightness and transparency, of the materials to be recovered. Western Anatolian Na-feldspars, which are the subject of this study, contain light- and dark-colored, transparent and opaque components, similar to the impurities in the food sector.

Western Anatolian Na-feldspars come from the Aydın, Çine, Gördes and Milas (Muğla) regions. The material is light-colored gneisses and albitic migmatites of the Menderes metamorphic massif. Albites (Na-feldspar) in migmatitic formations are white in color and mostly pure. There is no need for any enrichment process for such sections, because such raw material zones contain more than 9% Na_2O at worst, even reaching 11%.

Na-rich raw materials associated with gneisses (practically albite gneisses) contain opaque iron oxide minerals, rutile, black and white micas (muscovite, biotite) and tourmaline. It is very easy to separate opaques, biotite, rutile and tourmaline from the parent material by the optical method. However, it is somewhat difficult to distinguish between minerals that are similar in color, such as quartz and feldspar.

The optical enrichment method can successfully separate dark- and light-colored components from each other, but it is problematic for minerals with the same color and luster. The textural properties of the starting material are also important. In particular, the grain liberation size appears to be a very significant factor.

The Na-feldspar sample enriched in this study was taken from aforementioned regions. After mineralogical and petrographic analyses were performed on the samples, grain liberation sizes were determined by grinding and the samples were made ready for optical enrichment. After a series of processes, a significant enrichment in Na-feldspar ratio was achieved.

With this method, gneisses with low albite content, which are not yet in use, will become usable and it will also be possible to use raw materials that are discarded as waste. Optical enrichment processes will ensure the long-term sustainability of Western Anatolian Na-feldspar resources.

MATERIAL AND METHODS

MATERIAL

In order to investigate the optical enrichment aspects of the Western Anatolian feldspars, we collected four representative samples from the Aydın, Çine, Gördes and Milas (Muğla) areas (Fig 1). At least 100 kg sample was prepared for the enrichment tests.

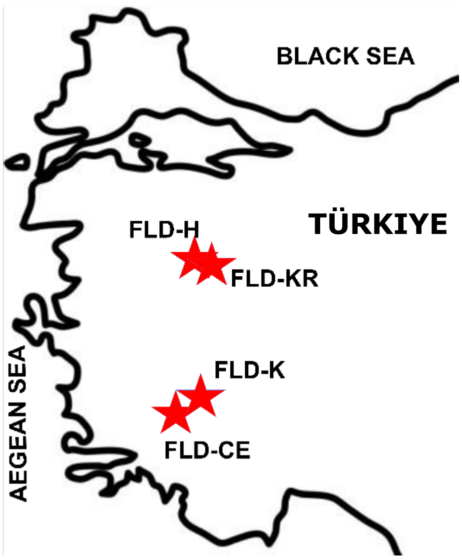

Fig 1. *The locations on the Google earth image of the samples studied.*

METHODS

The chemical compositions of the raw material were determined with an XRF spectrometer Panalytical Axios. Samples were dried at 105 °C for 2 h. After that, 1 g dried sample was fired at 1000 (±50) °C to determine the loss on ignition (LOI) in accordance with the EN 15309 standard. Samples were prepared as fused beads for XRF, initially. Fused beads were created by mixing a finely powdered (<63 μm) sample with a flux (lithium tetraborate/metaborate mixture) in a flux/sample ratio of 9:0.9 and then heated to 1050 °C in a platinum crucible.

The mineralogical composition of the raw material was determined with a PANalytical X'Pert Pro MPD diffractometer. XRD data were collected in a Bragg–Brentano (θ/θ) vertical geometry (fast reflection mode) between 3° and 70° 2θ) in steps of 0.02° 2θ and step-counting time of 1 s. The X-ray tube (Cu Kα radiation) operated at 45 kV and 40 mA. A 1/2° divergence slit, a soller slit (0.04 rad) and a 10-mm fixed mask were mounted in the incident beam pathway. The Rietveld method was used to determine the quantitative XRD results.

Optical microscopy is based on the interaction of light with minerals. In the feldspar sample it was observed how light interacts with albite, mica, quartz and amphibole minerals under a Leica Optical microscope.

The sizes and shapes of the minerals in the feldspar were examined with a Leica DM750O model polarizing microscope. An X-rite SP62 color meter was used for color measurements. A CIMBRIA SEA TRUER (5 channels) optical sorting device was used to separate dark-colored minerals, mica and quartz in the Na-feldspar. Optical sorting is the automated process of sorting raw material products using cameras and/or lasers. Depending on the types of sensors used and the software-driven intelligence of the image processing system, optical sorters can recognize an object's color, size, shape, structural properties and chemical composition.

EXPERIMENTAL

PETROGRAPHY

Before grinding the materials, 5 thin sections were prepared for the representative samples. They were then examined by the polarizing microscope. These studies revealed that the materials are micaceous gneiss, leucocratic para-gneiss and albitic gneisses (Figs 2a-d). The banded and gneissic schistosity texture are recognized (Figs 2a, b, c). Beside these, cataclastic augen and porphyroblastic textures are described. These rocks are formed mainly from the quartz, feldspars (Na- and K-feldspars), biotite and muscovite micas together with the subordinate amount of black colored tourmaline, opaques (iron oxide) minerals, sphene, rutile and zircon paragenesis (Figs 2a-c). The feldspathic gneisses from the 4 areas of Western Anatolia are commonly interfingered with the two-mica schists (Fig 2d). For this reason, contamination by mica and iron oxides occurs during mining activities of the feldspathic raw materials.

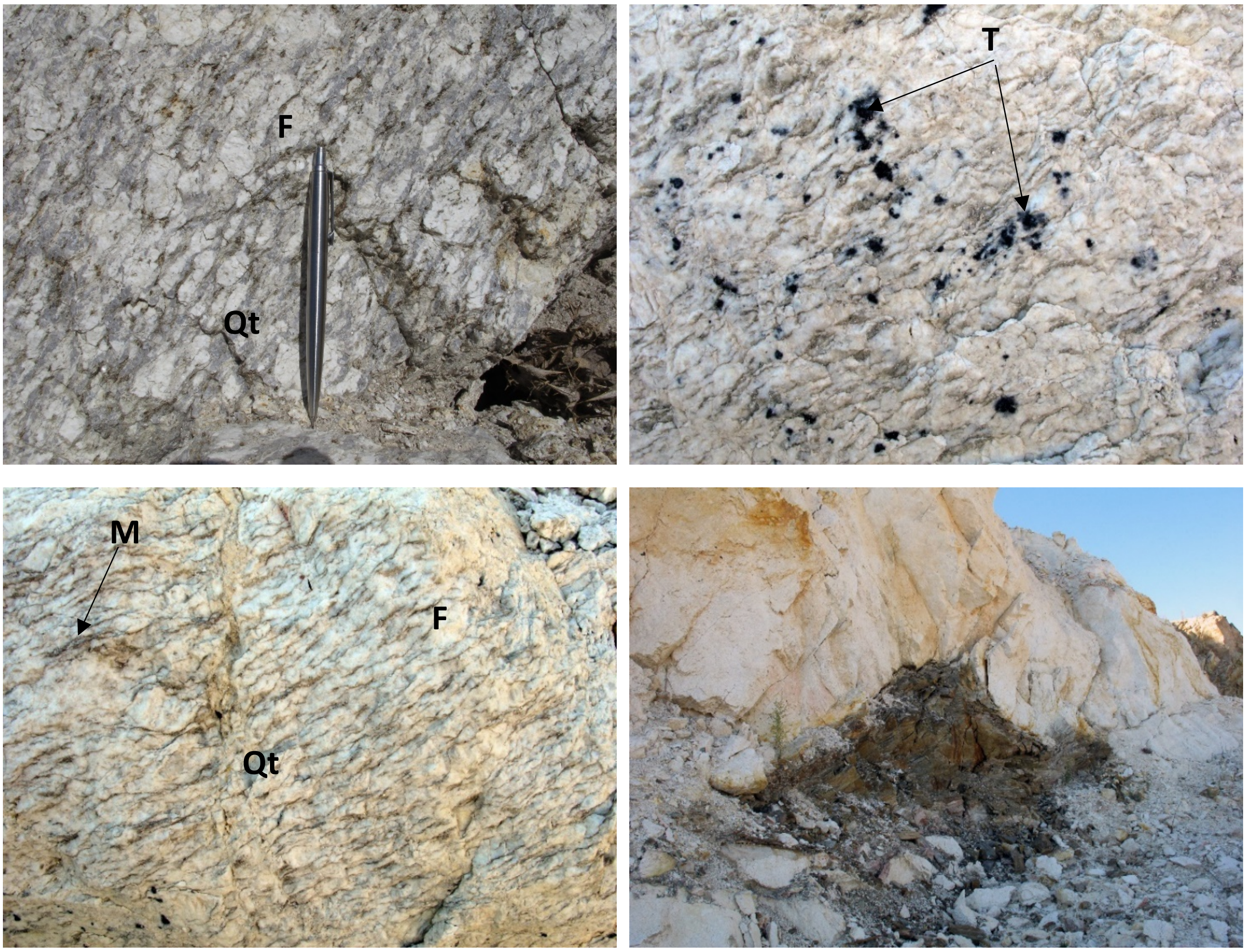

Fig 2a, b, c, d. *Close-up views from the Western Anatolian feldspathic gneisses (a, b, c) and the outcrop view from the albitites (d) (Qt: quartz, F: feldspars, M: biotite, T: tourmaline).*

OPTICAL SEPARATION

Raw materials such as feldspars, granite, quartz and kaolin used in the ceramic industry inherently contain impurities in their structures. These structures, which are rich in iron, titanium and metal, reduce product quality. In order to eliminate these impurities, there are different enrichment methods [2]. The optical sorting or enrichment method is one of them. In this study, the optical separation method was used to ensure the use of feldspar resources, which are limited in use due to their low Na_2O value.

Optical sorting helps to improve product quality, maximize yield and increase throughput while reducing labor costs.

The development of optical sorters has occurred simultaneously with the advancement in technology. Optical sorting allows granular particles to be separated from each other due to differences in light reflectivity, color and transmittance. Due to these properties, optical sorters are used in a wide range of applications, from mining and waste treatment to the food industry [3, 4, 5, 6].

The main benefits of optical sorting are listed as follows [7]: a) Reduction of energy consumption, b) Efficient use of mineral resources, c) Reduction of water requirements, d) Reduction of environmental impact, and e) Quality increase.

The optical separation/sorting method, which is faster, cheaper and easier than the flotation method, was used to separate impurities such as iron, mica and tourmaline in Western Anatolian feldspars. A SEA TRUER model 5-channel machine developed by SEA CIMBRIA ®Italy located in NTS machinery Mersin (Türkiye) laboratories was used.

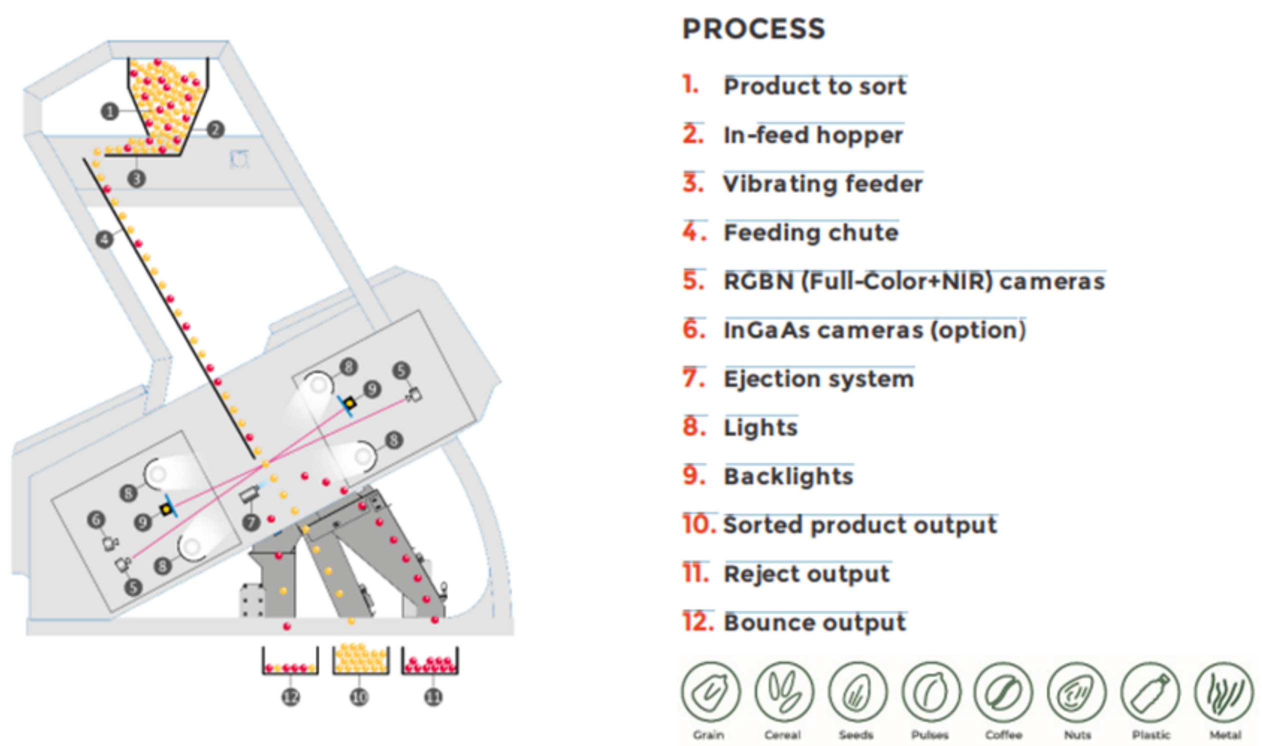

Fig 2. *General schema of the Sea Truer optical sorter [8]*

The equipment consists of a feed pan and flow plate, line scan camera/sensor, air blowing valves (nozzle) and light sources (Fig 2). The efficiency of the system rests on the combination of real color, particle size, brightness and shape criteria [5, 9]. The number of cameras and the type of sensors to be used are selected according to the type of material to be sorted. Scanning speed varies with the grain size of the material. Images taken with the integrated visible light-sensitive camera are transferred to the software with RGB (red, green, blue) coding. Optical sorting is performed on a particle basis. Although sorting is theoretically possible with particles down to 0.5–1 mm by the use of high–resolution cameras, it is not widely preferred in mineral processing because of capacity reduction. Applications above 10–20 mm are preferred for economic and technical reasons.

3. RESULTS AND DISCUSSION

3.1. SAMPLE CHARACTERIZATION

The raw materials were initially crushed using a laboratory type jaw crusher and reduced to a particle size below 10 mm. Subsequently, the crushed sample was dried at 120°C to constant weight. Chemical and mineralogical analyses were carried out on these materials with the XRF and XRD methods.

The chemical analysis results are given in Table 1 for the 4 studied samples.

	Content %									
Sample	**LOI**	**SiO_2**	**Al_2O_3**	**TiO_2**	**Fe_2O_3**	**CaO**	**MgO**	**Na_2O**	**K_20**	**P_2O_5**
FLD-K	0.4	66.96	19.27	0.54	0.27	1.81	0.72	9.04	0.48	0.25
FLD-H	0.73	72.46	16.31	0.12	0.39	0.58	0.06	4.66	4.44	
FLD-KR	0.42	72.69	15.92	0.17	0.3	0.28	0.01	4.73	5.35	
FLD-CE	1.24	68.71	17.56	0.47	0.67	0.63	0.66	8.57	0.95	0.35

Table 1. *Bulk chemical analysis of the felspathic raw materials (the references FLD-K, -C, -H,-KR and -CE indicate the samples come from the different areas. LOI: loss on ignition).*

It is clear from Table 1 that the raw materials have variable chemical compositions. Especially Na_2O and K_2O depend on the Na- and K-feldspar, respectively, iron oxide is characterized by the Fe_2O_3 contents. MgO and some of the Fe_2O_3 originate from black micas such as biotite and phlogopite. In order to test this assumption, we have carried out an XRD analysis on these materials (Fig 3). Table 2 shows the XRD results for the materials given in Table 1. Quartz, albite (Na-feldspar), orthoclase (K-feldspar), and partly muscovite are the main constituents. Table 2 also indicates the source of iron and magnesium as Fe-mica (commonly biotite and phlogopite).

	FLD-K	FLD-H	FLD-KR	FLD-CE
Quartz	3.1	36.83	34.6	10.67
Albite	86.12	33.62	36.78	81.7
Orthoclase		23.36	17.81	1.26
Muscovite	1.59	5.34	6.94	5.75
Fe-mica	1.48			
Chlorite	3.78			
Tourmaline	0.2	0.86		
Ti mineral				
Amphibole	0.61			

Table 2*. XRD results of the samples which are given in Table 1.*

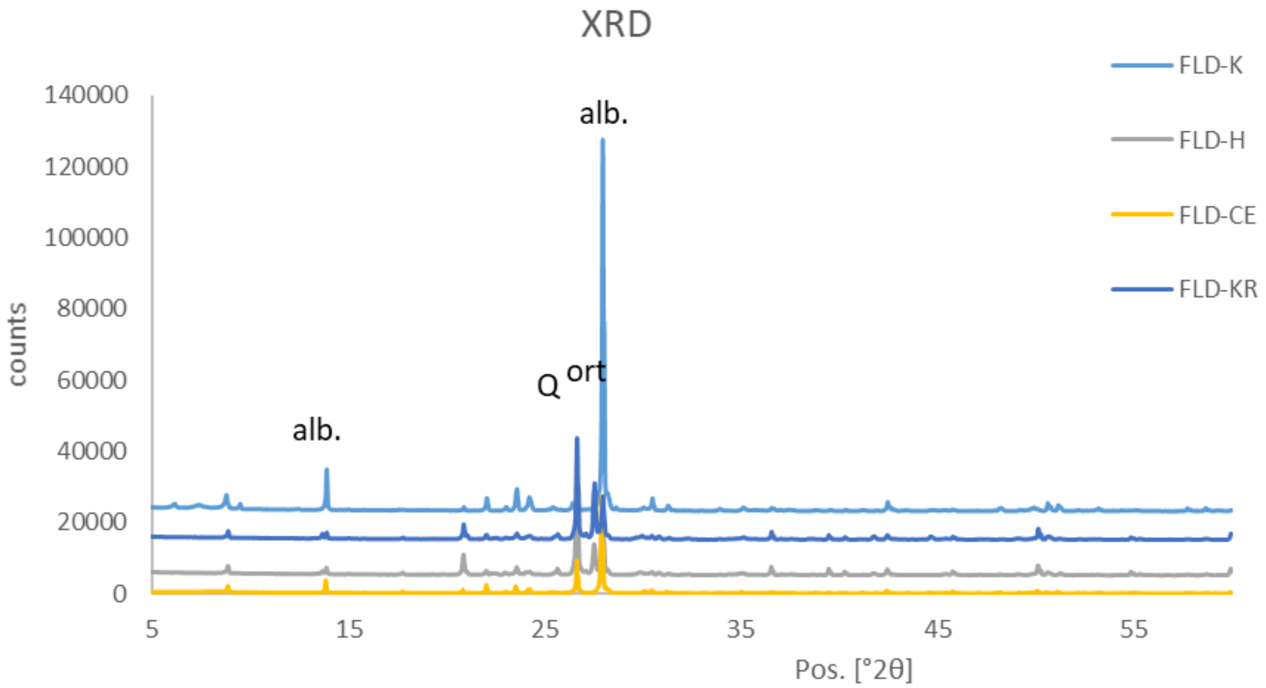

Fig 3. *XRD diagrams for the 4 feldspar samples from Western Anatolia. Q : Quartz – Alb : Albite – Ort : Orthoclase – m: mica minerals (muscovite -biotite- phlogopite).*

In order to obtain good results from optical sorting, the grains must be free from each other. For this purpose, feldspathic raw materials were ground and sieved to different sizes and each of these fractions was chemically analyzed (Table 3). Sieve analysis was performed on samples sized smaller than 10 mm.

Sieve residues were examined with an optical binocular microscope. The data from the microscope studies were as follows: transparent to semitransparent, glassy luster and colorless grains are quartz; opaque black grains were iron oxides and titanium minerals; pinkish colored ones are K-feldspars; dull white grains are Na-feldspars, transparent colorless flakes muscovite and dark brown to greenish shiny flakes are biotite and phlogopite (Figs 4a-h).

		LOI	SiO_2	Al_2O_3	TiO_2	Fe_2O_3	CaO	MgO	Na_2O	K_2O	P_2O_5
FLD -K	+2 mm	0.5	74.33	15.07	0.44	0.15	1.34	0.4	6.95	0.38	0.18
	-2 mm + 1mm	0.56	69.95	17.4	0.79	0.25	1.58	0.66	7.82	0.51	0.23
	-1 mm + 500µm	0.58	67.16	19.1	0.7	0.21	1.68	0.71	9.07	0.45	0.2
	- 500µm + 250µm	0.42	66.48	20.08	0.33	0.14	1.71	0.44	9.74	0.35	0.11
	- 250 µm	0.73	65.44	19.76	0.39	0.39	2.01	0.87	9.14	0.56	0.37
FLD -H	+2 mm	2.72	75.89	13.11	0.11	0.37	0.45	0.09	3.02	3.99	
	-2 mm + 1mm	0.74	77.65	13.48	0.09	0.45	0.64	0.09	3.76	2.96	
	-1 mm + 500µm	1	75.48	14.66	0.23	0.5	0.88	0.1	4.47	2.44	
	- 500µm + 250µm	1.12	71.36	17.12	0.25	0.68	1.26	0.16	5.58	2.2	
	- 250 µm	2.03	66.06	20.16	0.34	1.14	1.48	0.2	6.31	2.01	
FLD-KR	+2 mm	0.38	81.37	10.93	0.15	0.15	0.18	0.01	3.32	3.25	
	-2 mm + 1mm	0.54	79.39	12.4	0.17	0.39	0.26	0.05	3.98	2.6	
	-1 mm + 500µm	0.43	78.87	12.8	0.06	0.56	0.32	0.06	4.24	2.29	
	- 500µm + 250µm	0.61	76.22	13.96	0.16	0.82	0.4	0.08	5	2.29	
	- 250 µm	0.75	75.88	14.23	0.18	0.8	0.39	0.06	4.99	2.3	
FLD -CE	+2 mm	1.17	69.15	17.72	0.33	0.51	0.62	0.44	8.49	1.04	
	-2 mm + 1mm	1.11	71.47	16.5	0.17	0.37	0.58	0.3	7.56	1.27	
	-1 mm + 500µm	1.21	68.89	17.74	0.55	0.51	0.66	0.52	8.43	1.03	
	- 500µm + 250µm										
	- 250 µm										

Table 3. *Results of the sieve analysis and the chemical analysis for different grain size materials between +2 mm and 250 µm.*

Sieve analysis indicated that the grains larger than the 1 mm contain a number of minerals in a single grain (Figs 4a, c, e, g). In contrast, the grains in -1 mm +500µm size have been freed from each other as seen on Figs 4b, d, f, h. Narrow particle size distribution is essential to increase separation efficiency during an optical sorting operation. Therefore, the conditions maintaining a 1/3 ratio between the smallest and the largest particle sizes are preferred for an effective separation [10, 11]. We have evaluated the sieve analysis together with the chemical analysis results together and decided to use the grain size range of -1 mm +500µm.

Fig 4a-h. *Binocular microscope views of sieved materials of different sizes (left-handed views show the + 1 mm; right-handed images display the -1 mm to +500μm grain sizes (a, b: FLD KR, c, d: FLD-H, e, f: FLD-K, g, h: FLD-CE).*

The opaque and dark-colored minerals, mica, feldspar and quartz grains were separated and collected from the crushed raw materials with the help of a polarizing microscope. Beside this, the light transmittance features of the minerals were determined by polarizing microscope. Some dark grains were classified as opaque and others as translucent. The opaque ones were the ore minerals such as hematite, limonite, pyrite. The others were silicate minerals. For each raw material, opaque, dark-colored, transparent and dull grains were introduced into the optical sorting machine's software. After that different size materials (see Table 3) were fed into the optical sorting device, and the machine was started.

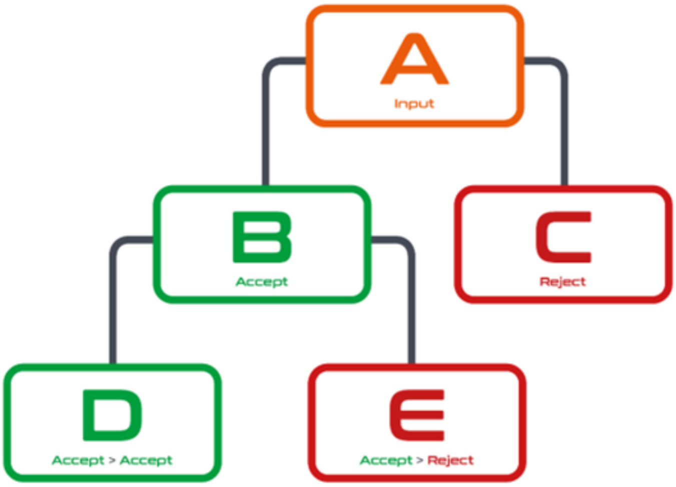

Fig 6. *Sorting system of the CIMBRIA SEA TRUER device.*

The optical sorting systematics is given in Fig 6. According to this scheme, the opaque and dark-colored minerals ("C" in Fig 6) were separated from the bulk sample. The dark-colored and opaque mineral-free batch was subjected to the second stage process ("B" in Fig 6).

During this stage, the light-colored, and transparent/semitransparent (quartz) and dull (matte) light-colored mineral (feldspars) separation was performed.

Some difficulties were experienced during the optical sorting. Two main issues were as follows: a) if the fine-sized dark-colored and the light-colored minerals exist in a single grain, the device separated this grain as dark-colored, and eliminated it. b) some pinkish K-feldspars were sorted as dark-colored mineral. Similar to this, some feldspars could not be separated from the quartz. Surface color homogeneity and grey color toning are not well perceived, leading to this problem [12, 13, 14]. In order to solve this, the samples were fed into the machine again, and the process was run one more time.

The four feldspar samples optically sorted with the scheme are shown in Fig 6, and all the materials were chemically analyzed (Table 4). Table 4 revealed that the "D" stage of optical sorting is best for the total alkali contents ($Na_2O + K_2O$) in terms of the Na- and K-feldspars.

		LOI	SiO_2	Al_2O_3	TiO_2	Fe_2O_3	CaO	MgO	Na_2O	K_20	$Na_2O + K_2O$
FLD-K	A	0.93	65.17	19.52	0.5	0.43	1.67	1.22	9.3	0.75	10.05
	B	0.62	66.37	19.45	0.53	0.18	1.55	0.52	9.48	0.68	10.16
	C	0.48	66.76	19.02	0.52	0.32	1.58	0.55	9.08	1.01	10.09
	D	1.9	64.63	19.55	0.28	0.02	2.46	0.36	9.90	0.38	10.28
	E	0.50	76.1	13.19	0.18	0.4	0.42	0.05	3.12	5.77	8.89
FLD-H	A	0.52	75.28	14.4	0.02	0.3	0.52	0.02	3.56	5.13	8.69
	B	0.53	73.25	15.11	0.21	0.11	0.46	<0.005	3.5	6.49	9.99
	C	0.62	76.73	13.55	0.24	0.64	0.46	0.1	3.35	4.24	7.59
	D	0.32	70.32	16.47	0.09	0.04	0.48	<0.005	3.35	8.56	11.91
	E	0.5	75.77	14.03	0.24	0.47	0.47	0.05	3.28	5.04	8.32
FLD-KR	A	0.38	76.28	13.94	0.19	0.27	0.31	<0.005	3.94	4.68	8.62
	B	0.53	73.94	14.94	0.33	0.42	0.34	0.01	4.48	4.95	9.43
	C	0.45	74.62	14.74	0.18	0.59	0.39	0.03	4.69	4.18	8.87
	D	0.39	72.94	15.52	0.2	0.06	0.32	<0.005	4.28	6.26	10.54
	E	2.25	63.41	23.26	0.36	0.48	0.19	0.06	3.16	6.87	10.03
FLD-CE	A	1.24	68.71	17.56	0.47	0.67	0.63	0.66	8.43	0.95	9.38
	B	1.21	68.89	17.74	0.17	0.37	0.66	0.52	8.57	1.03	9.6
	C	1.11	71.47	16.5	0.55	0.51	0.58	0.3	7.56	1.27	8.83
	D	0.52	69.06	18.98	0.53	0.21	0.47	0.17	9.57	0.33	9.9
	E	1.1	69.15	17.72	0.33	0.4	0.62	0.44	8.01	1.04	9.05

Table 4. *Chemical analysis results of the materials obtained after each optical sorting stage (A to E in Fig 6).*

After the optical sorting process, cone firing was performed under 1200°C for 60 min in a laboratory furnace, and color measurements were taken from the samples. The specular reflection index of each sample was measured in terms of the chromatic coordinates L* (whiteness), a* (red-green), b*(yellow-blue) with an X-rite SP 62 color measuring device. The color parameters are given in Table 5.

		L	a	b					
FLD-K	A	64.23	0.56	12.89	FLD-H	A	73.74	2.33	15.09
	B	67.26	1.55	16.58		B	73.71	1.18	13.46
	C	61.86	0.38	12.05		C	56.47	4.06	18.09
	D	**80.32**	**1.58**	**20.13**		**D**	**75.76**	**1.09**	**13.89**
	E	63.4	0.53	13.21		E	70.21	0.39	17.47
FLD-KR	A	69.85	2.17	19.29	FLD-CE	A	70.73	0.33	8.68
	B	73.3	1.68	8.45		B	74.77	0.1	9.48
	C	60.93	3.49	16.99		C	68.86	1.4	14.75
	D	**74.59**	**1.01**	**8.04**		**D**	**75.85**	**0.09**	**9.3**
	E	71.85	3.00	16.06		E	68.54	0.14	10.89

Table 5. *Color (L*, a*, b*) values of the fired cones which are formed from each of the individual 4 feldspar samples.*

CONCLUSIONS

In this study, the separation of minerals such as opaque iron oxides, tourmaline and mica contained in western Anatolian Na-feldspars was carried out by an optical sorting method. For this process, firstly, the materials were ground to suitable grain sizes where the grains could be freed. Then a 4-stage optical sorting process was applied. In the first stage, dark-colored minerals (biotite, phlogopite, amphibole, etc.) and opaque iron oxide minerals in the raw materials were separated. Then, light-colored minerals were separated. Here, quartz and feldspars were separated from each other, especially considering their light transmittance and transparency properties. With this four-stage optical sorting process, feldspathic natural raw materials taken from 4 different locations in Western Anatolia were enriched in terms of total alkali element oxides such as Na_2O and K_2O. FLD-K and FLD-CE samples were not enriched to the desired extent. The initial total alkali content was 10.05%. After the 4-stage enrichment process, this value increased slightly to 10.28%. However, when the results are analyzed, it is seen that the albite (Na-feldspar) component is enriched while the K-feldspar component is impoverished.

This indicates that the K-feldspar phase could not be recovered. The probable reason for this is that K-feldspars are pinkish in color due to their iron content, and the optical sorting device detects this and separates them to the dark-colored mineral side. In contrast to the others, FLD-HK and FLD-K samples were able to enrich at satisfactory rates. As a result of the treatments, the initial total alkali values increased from 8.69 to 11.91 and from 8.62 to 10.54.

Effective adjustment of the sample feed rate, well-sieved and dust-free samples improve camera detection and results. As a result, the optical separation method, which is used in the food industry, especially in the extraction of unwanted components such as stones from cereals, can also be successfully used in the enrichment of feldspathic raw materials.

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