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Upgrading of Sillimanite and Garnet Ores to Improve Their World Market Competitiveness

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Abstract: Sillimanite is industrial mineral used in the manufacture of refractory bricks and high-temperature crucibles, as abrasive wear. Large well crystalline sillimanite is recorded in sillimanite-kyanite pelitic and semipelitic schists located at eastern of the the northernmost part of dome of Wadi Hafafit Culmination between latitudes 24° 44' 33" and 24° 51' 30" N and longitudes 34° 26' 50" and 34° 33' 45° E. The Migif-Hafafit gneisses and schists comprise psammitic and migmatitic gneisses and pelitic and semipelitic schists which contains the sillimanite refractory materials. Such rock forms a zone of 20-60 m in width and 4.5 km in length. The scope of work is application of mineral processing methods to concentrate the refractory minerals chiefly sillimanite from this Hafafit sillimanite pelitic and semipelitic schist. Besides, these schists are also garnet-bearing and is involved during beneficiation processes. The studied area is occupied by the Migif-Hafafit gneisses and schists.

Key words: Upgrading, Sillimanite, Garnet, Hafafit Schist.

INTRODUCTION

Sillimanite with kyanite is a chief member of the sillimanite industrial material. Sillimanite is industrial mineral used in the manufacture of refractory industries. This material is prized chiefly for its refractoriness that is used in acid refractory products (mortars and castables), bricks, abrasive wear and high temperature crucibles. Garnet is widely used in the manufacture of a medium hard abrasive paper and abrasive cloths. Today, the vast majority of garnet is used as an abrasive blasting material, for water filtration, in a process called water jet cutting, and to make abrasive.

The exposed rock units in the study area are psammitic gneisses, pelitic and semipelitic schists, the ultramafic rocks, the ophiolitic metagabbros, intrusive metagabbros, diorite, tonalite, the granitoid-type, dykes and veins (Fig.1). The pelitic and semipelitic schists are subdivided into the following varities biotite: schists, almandine-mica schists, kyanite-sillimanite-mica schists, sillimanite-garnet-biotite schists, sillimanite-garnet schists and mylonitic pebbly schists (Hassan *et at.*, 2008).

The Al_2O_3 percentage in this zone of the pelitic and semipelitic schist ranges from 16.49 to 15.56 % (Hassaan *et al.*, 2008). The scope of the present study is application of mineral processing techniques to separate the sillimanite to obtain upgraded material in which Al_2O_3 content matches well with the standard sillimanite refractory material (52 %). Moreover, garnet as by-product will be also separated for its industrial applications.

MATERIALS AND METHODS

Beneficiation and upgrading of sillimanite and garnet from the pelitic and semipelitic schists to improve their world market competitiveness will be undertaken by steps outlined and practiced in the Central Metallurgical Researching and Development Institute (CMRDI). In a general way, the scope of sillimanite and garnet processing is twofold; it is objected being to eliminate either (1) unwanted chemical species or (2) particles of unsuitable size or structure. The principal applied process involved in the preparation of mineral

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particles from a chemical standpoint is separation of chemically dissimilar particles using crushing, grinding, magnetic separation and gravity separation.

Materials:

Two bulk samples each weighing 100 kg from the zone of sillimanite and garnet bearing schists were collected to carry out the study.

Methods:

The processes that are chiefly adopted for sillimanite and garnet processing include the following:

Hand Picking or Hand Sorting of Sillimanite and Garnet:

The two sillimanite and garnet (present as almandine) schists samples washed to remove the obscuring dust and the dirt from the surface of the ore pieces. The washing action facilitates the recognition of minerals in performing hand picking. Sorting or hand-picking distinct from the more extensive mechanical processing is the separation of both constituents by hand, taking advantage characteristic appreciated by the eye, namely color, luster, and appearance. The aim of this operation is pick out pieces of ore clean enough for industrial uses. White sillimanite, yellowish brown sillimanite and greyish green sillimanite crystals were separated by hand from the two samples. Garnet was separated from the schists exist in the study area and one sample of almandine garnet was obtained.

Crushing and Grinding Circuit of Sillimanite and Garnet:

Size reduction, or comminution, is an important step in the processing, in that it may be used to produce particles of the required size and shape, to liberate valuable minerals from gangue so that they can be concentrated and to increase the surface area available for chemical reaction. Primary crushing of sillimanite and garnet lumps was conducted in the “Denver” type jaw crusher, 300X250 mm to produce feed passing 100 % from size 2.5 cm in diameter. Secondary crushing was performed by “Denver” type roller crusher with roller dimensions 300 x 250 mm. Sillimanite and garnet schists were crushed in a closed circuit and the position of roller was varied to give products 100 % passing 3.36 mm sieve to prepare feed for the grinding process.

Size analysis and Liberation study:

Two selective samples from the secondary crushed sillimanite and garnet were taken in order to make size analysis and liberation studies. It was sieved on a sieve series varied from 3.36 to 0.075 mm sieve size. The liberation study of the sieved products was conducted by making mounted slides of the different size fractions and studied using polarizing microscope as opaque (ore minerals) and transparent / translucent (gangue) minerals. The method depends upon counting the free mineral particles and the locked particles. As the number of counted particles increased, the accuracy of the method increased. So, 500 to 600 total particles are recorded in each size fraction.

Grinding of Sillimanite and Garnet:

Grinding experiments were carried out in wet conditions in a “Wedag” rod mill 15.1 cm in diameter and 30 cm in length at a rotation speed of 75 rev min^{-1}; the rods were 1.1 cm in diameter and 29 cm in length. Two wet grinding schemes for the grinding process were suggested. The first one involves grinding representative sample about 512 g with 512 ml water and 12 rods for period varied from 2 to 10 min at 40 % mill filling and 50: 50 solid /liquid ratio. The ground products were used for size analysis. The second one involves grinding the material in closed circuit using “Wedag” (15.1 X 30 cm.) rod mill and sieve with opening 0.417 mm. Grinding was carried out for 10 min at 40 % mill filling and 50:50 solid / liquid ratios. A 512 g test sample was loaded with 512 ml water and 12 rods weighing 9 kg. After the end the ground sample was discharged and wet screened on 0.417 mm sieve to pass 100 % and the over size returned back to the mill and completed to same weight for another grinding cyclic. Grinding of sillimanite and garnet was carried out in closed circuit using "Wedag" rod mill and sieve with size 417 micron to prepare feed for separation process. Table 4 represents the results of grinding and mineralogical analysis of sillimanite bearing schist in size fraction – 417 + 75 micron and the size fraction less than 75 micron.

Magnetic Separation:

Magnetic separation was carried out on the size fraction – 0.417 + 0.075 mm using different magnetic separators such as Magnaroll, Carpco, Cross belt magnetic separator and rare earth three stage magnetic separators.

Magnetic separation of size fraction – 417 + 75 micron for both sillimanite and garnet ore were carried out using "Dings" high intensity magnetic separator, "Carpco Induced roll?" Magnaroll and "Eriez" rare earth three stage magnetic separators.

The mechanism of separation using Cross Belt High Intensity Magnetic Separator depends on the principle of selective picking up of paramagnetic particles against the force of gravity, and leaving the non-magnetic particles on the belt.

The magnetic separation of sillimanite and garnet at size fraction - 417 + 75 micron were carried out using "Carp co" magnetic separator at different drum speed. The forces involved in making the separation are not only magnetic force but also that of gravity, centrifugal force, and the friction of the air against the particles.

The principle mechanism of magnetic separation of sillimanite and garnet was realized using Rare Earth Three stage Magnetic Separator based upon high magnetic pulley or roll attract and hold magnetic particles on the surface of a thin non magnetic belt passing over the pulley, thereby altering the discharge trajectory of these particles. Non-magnetic particles in the same mixture are not attracted by the roll, and therefore discharge in a normal trajectory under the influence of belt motion, centrifugal force and gravity. The difference in discharge trajectories of two classes of particles enables a separation to be made. It contains three magnets for cleaning the non-magnetic fraction.

Two separation schemes of both sillimanite and garnet bearing schists were carried out. The first one is using one separation unit to separate magnetic fraction and non-magnetic. The non-magnetic fraction was further cleaned with the magnetic unit. The second is using the three magnetic units.

Gravity Separation of the Magnetic Fraction of Garnet:

It was undertaken using shaking table based on the difference in the specific gravity between the minerals on the magnetic fraction of garnet bearing schist in order to separate mica and clay fraction.

Chemical Analysis:

The chemical analysis of sillimanite ore, garnet ore, ground products and separated fractions by physical methods were carried out using XRF technique for the two bulk samples and X-ray diffraction for the separated samples to determine both minerals as semi-quantitative method.

RESULTS AND DISCUSSION

X-ray Diffraction and Chemical analysis of Sillimanite and Garnet bulk samples:

The results of the XRF analysis of the two bulk samples are given in Table (1). The X-ray diffraction pattern of sillimanite-bearing schists (Table 2) recorded presence of sillimanite, quartz, albite, corundum, magnetite, K-feldspars, biotite, muscovite, almandine and kaolinite minerals. The results of the analysis shown in Table (2) recorded about 25 % sillimanite mineral. The X-ray diffraction of garnet-bearing schist showed presence of almandine, mica, quartz, plagioclase, magnetite, chlorite, actinolite, kaolinite and K-feldspar. The XRD analysis of garnet-bearing schist (Table 2) shows that it contains about 27.6 % garnet mineral.

The chemical analysis of the separated white, yellowish brown and greyish green sillimanite crystals (Fig.2) and garnet crystals are listed in Table (3). The standard chemical analysis of pure sillimanite contains 61.87% of Al_2O_3 and 36.72 % of SiO_2 (Deer *et al.,* 1962). The separated sillimanite contains low content of Al_2O_3 (31.03%) and high content of SiO_2 (58.03%). The high content of SiO_2 is due to that the separated sillimanite crystals are locked with quartz particles. The increased K_2O content due to partial alteration of sillimanite to muscovite along their margins caused decrease of Al_2O_3 content (Hassaan *et al.*, 2008).

Crushing and liberation studies of Sillimanite and Garnet:

Fig. 3 illustrates the size distribution, liberation percentage and sillimanite percentage. The d_{80} and d_{50}

of the crushed sillimanite were 3000 and 1168 micron respectively.

Table 1: The XRF analysis of the two bulk samples of sillimanite (26F, 26G, 21B, 25A) and garnet (36A, 37A).

Oxides	26 F	26 G	21 B	25 A	36 A	37 A
SiO_2	77.22	76.27	65.70	73.17	77.71	73.22
Al_2O_3	15.49	14.67	16.49	15.56	11.41	12.00
TiO_2	0.06	0.05	0.05	0.05	0.31	0.72
Fe_2O_3	0.87	0.79	0.93	1.06	2.64	3.90
FeO	0.78	0.71	0.84	0.95	2.38	3.51
CaO	0.92	1.04	1.09	0.88	2.37	1.68
MgO	0.42	0.45	1.13	0.92	1.10	0.89
MnO	0.061	0.012	0.016	0.008	0.041	0.023
Na_2O	3.05	3.06	0.64	0.43	1.83	3.25
K_2O	2.93	2.53	2.19	2.65	1.88	1.32
P_2O_5	0.088	0.085	0.11	0.062	0.04	0.30
L.O.I.	0.087	1.90	5.60	0.85	1.52	0.82
Total	102	101.6	94.28	96.59	103.2	101.6

Table 2: Mineral constituents from X-ray diffraction analysis of each of sillimanite (a) and garnet (b), bulk samples.

a-Minerals	Percentage	b-Minerals	Percentage
Sillimanite	25.06	Garnet	27.62
Quartz	32.54	Mica	9.45
Albite	24.48	Plagioclase	20.34
Almandine	1.75	Quartz	23.31
Biotite	4.26	Kaolinite	7.11
Muscovite	1.98	Chlorite	2.14
Corundum	2.50	Magnetite	3.28
Kaolinite	4.04	Actinolite	1.86
K-feldspar	2.11	K-feldspar	4.88

Table 3: Major oxide contents (in wt %) of sillimanite and almandine grains separated by hand sorting.

Oxides	1	2	3	I	4	II
SiO_2	59.72	61.86	52.5	36.72	38.83	37.39
Al_2O_3	30.72	27.97	35.07	61.87	10.14	20.72
TiO_2	0.02	0.02	0.02	-	0.54	0.16
Fe_2O_3	0.78	1.05	1.18	1.22	20.56	0.83
FeO	0.7	0.94	1.06	-	18.5	36.37
MnO	0.007	0.01	0.009	-	0.7	0.86
CaO	0.13	0.15	0.09	0.12	4.69	0.41
MgO	0.25	0.26	0.27	0.16	3.09	3.85
Na_2O	0.68	0.75	0.74	-	1.31	-
K_2O	6.32	5.08	7.56	-	0.21	-
P_2O_5	0.03	0.03	0.04	-	0.071	-
L.O.I.	4.2	3.2	3.62	0.24	1.35	-
Total	103.6	101.3	102.2	100.4	99.994	100.6

I. Sillimanite schist, Relli, Vizagapatam dostrict, India (Rao, 1955).
II. Almandine garnet-chlorite rock, Falun, Sweden (Menzer, 1928). Anal M.Bending.
1, 2, 3. Sillimanite grains.
4. Garnet grains.

It is noticed that the liberation percentage of sillimanite increases with decreasing the size. It reaches its maximum (about 90 %) at sizes varied from 417 to 147 micron. The percentage of sillimanite mineral increased from 84 % to 92 % in the size fraction varied from 589 to 200 micron and its distribution increased also to 12 %.

Fig. (4) shows that the d_{90} and d_{50} crushed garnet were 1168 and 417 micron respectively. It is seen also that the liberation percentage, garnet percentage and its distribution increases with decreasing size. In the size fraction varied from 417 to 200 micron garnet percentage changed from 88 % to 83 % respectively. In the mean time the liberation percentage of garnet changed from 90 % to 98 % in the size fraction varied from 417 to 75 micron. From aforementioned results it suggested to grind the sillimanite ore and garnet bearing schists to obtain 100 % sillimanite and garnet passing from sieve size 417 micron.

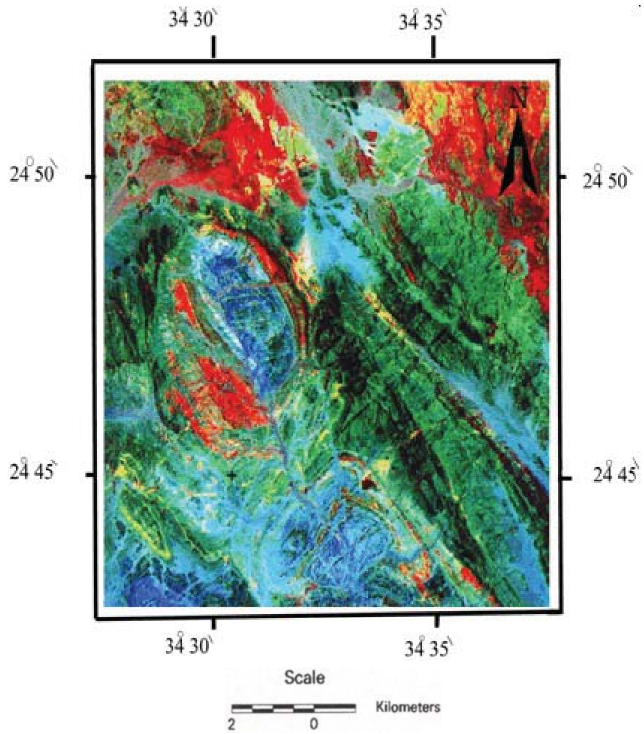

Fig. 1: Landsat TM ratio image (bands 5/7, 5/1, and band 4 in RGB) for the study area; illustrates the lithology as follows: ultramafics: (red), psammitic gneisses: (dark green), foliated metagabbros (light green) garnet-biotite schist: (purple) and granitic rocks: (bluish green).

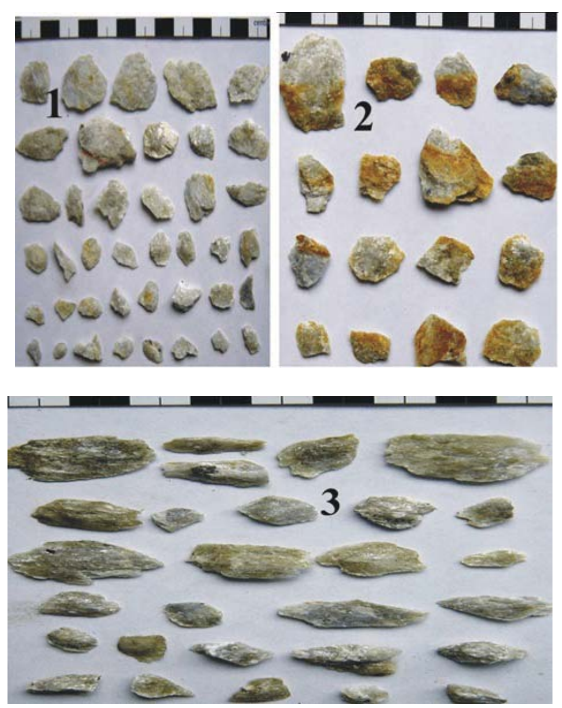

Fig. 2: Sillimanite crystals separated by hand sorting or picking, 1: white, 2: yellowish brown and 3: greenish grey crystals.

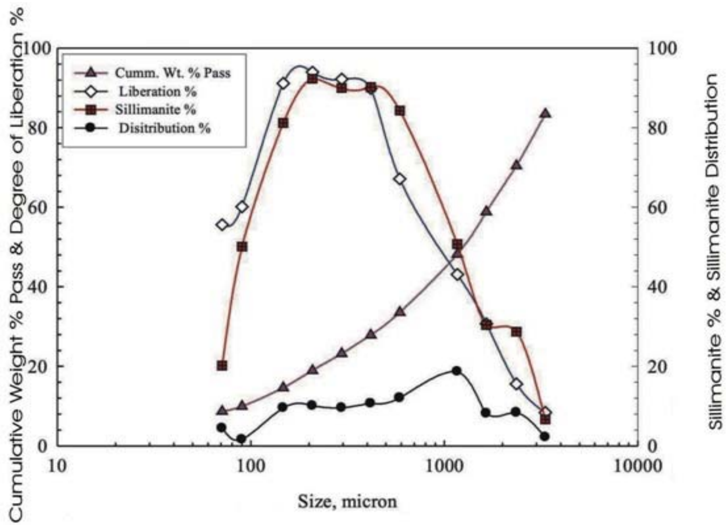

Fig. 3: Size anaclysis and liberation studies of sillimanite.

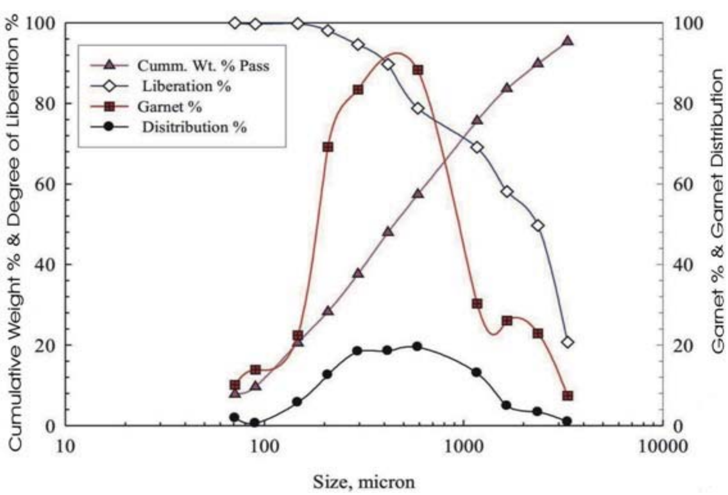

Fig. 4: Size analysis and liberation studies of garnet.

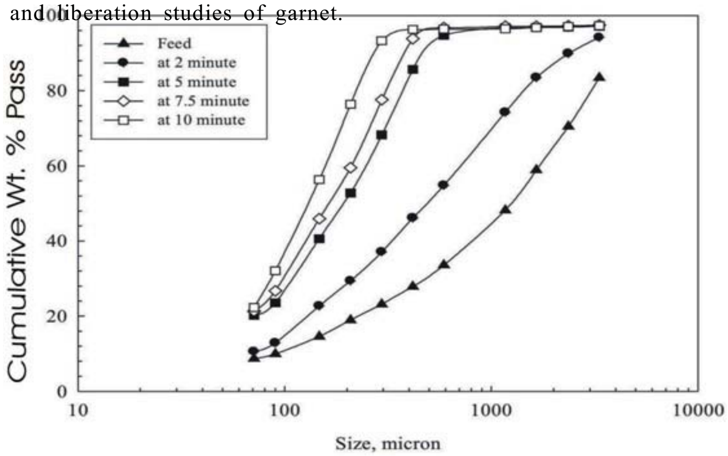

Fig. 5: Effect of grinding time on sillimanite.

Effect of Grinding:
Grinding Time on the Sillimanite and Garnet:

Fig. (5) illustrates the results of grinding the crushed sillimanite ore at different periods varied from 2 to 10 minute grinding time. The grinding of sillimanite and garnet ores increased with increasing the time of grinding. It is seen that in case of sillimanite the feed size changed from 83 % passing from sieve size 3327 micron to 86 % and 96 % passing from sieve size 417 micron at time varied from 2 to 10 minute respectively. The sillimanite mineral is concentrated in the size range from 417 micron to 150 micron. Therefore to reach this size it is suggested to grind the sillimanite ore for 10 minute grinding time.

Results of studying the grinding of garnet at different time periods (Fig. 6) shows that the feed size changed from 95 % passing from sieve size 3327 micron to 77 %, 99 % and 100 % passing from sieve size 417 micron at time varied from 2 to 10 minutes respectively. The garnet mineral is concentrated in the size range from 417 micron to 75 micron. Therefore, to reach this size it is suggested to grind the garnet ore for 7.5 minute grinding time. The non-magnetic fraction represents about 64 % by weight and was enriched with feldspar, quartz and kaolin. It could be considered suitable for ceramic industry.

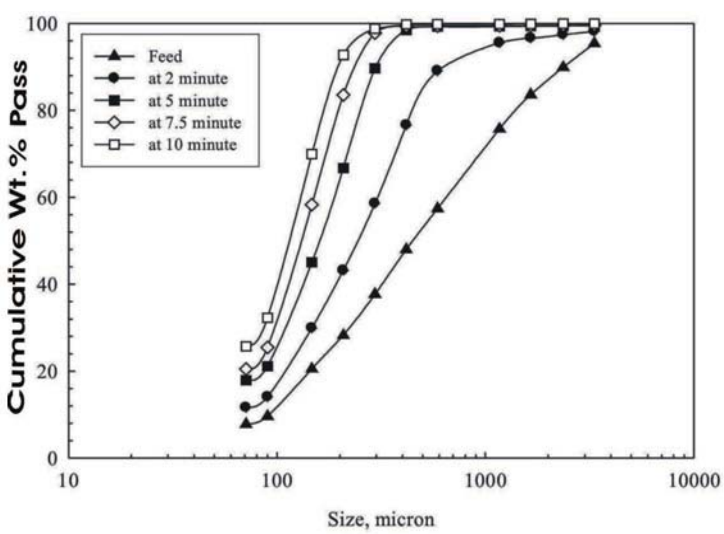

Fig. 6a: Effect of grinding time on garnet.

Table 4: Mineral constituents from X-ray diffraction analysis of each of garnet (a) and sillimanite (b) separated by grinding in closed circuit.

(a) garnet	Fraction, mm - 0.417 +0.075	-0.075	(b) sillimanite	Fraction, mm - 0.417 +0.075	-0.075
Minerals	Distribution % 96.22	3.78	Minerals	Distribution % 96.52	3.48
Wt %	75.38	24.62	Wt.%	92.16	7.84
Garnet	30.1	13.91	Sillimanite	28.59	12.1
Mica	5.91	20.31	Quartz	31.51	19.1
Plagioclase	24.7	13.13	Albite	23.85	0.01
Quartz	24.1	20.91	Almandine	3.79	1.3
Kaolinite	3.16	19.19	Biotite	2.83	21.1
Chlorite	2.19	2.0	Muscovite	1.27	10.3
Magnetite	2.61	5.32	Corundum	2.7	0.1

Actinolite	2.11	1.10	Kaolinite	1.31	36.1
K-feldspar	5.12	4.13	K-feldspar	2.29	0.001

Grinding in Closed Circuit:

Table (4) represents the mineral constituents by XRD method of grinding in the size fraction– 417 + 75 micron in closed circuit. The size fraction – 417 + 75 micron represents about 92 % by weight of sillimanite schist ore and enriched with sillimanite mineral (32%) with its distribution percentage of sillimanite about 97 %. The size fraction less than 75 micron represents about 8 % by weight with 12 % sillimanite. Results of grinding and X-ray diffraction analysis of garnet size fraction -417 + 75 micron and size fraction less than 75 micron (Table 3) show that the size fraction – 417 + 75 micron was about 75 % by weight with 32 % garnet mineral and 88 % distribution percentage. In the meantime the size fraction less than 75 micron represents about 25 % by weight with about 14 % garnet. The highest amount of fines reveals that the garnet ore is more friable than the sillimanite ore.

Dry High Intensity Magnetic Separation of Sillimanite and Garnet:

Cross belt High intensity Magnetic Separator:

Table (5) shows the results of magnetic separation of sillimanite at different magnetic fields. The magnetic fraction at magnetic field 13000 gauss represents about 2.5 % by weight which enriched with almandine, biotite and muscovite. The non magnetic fraction represents about 97.53 % by weight and contains 30.9 % sillimanite, 33.4 % quartz and 30 % albite. It will be further treated to separate quartz and albite using flotation technique in order to increase the grade of sillimanite.

The results of magnetic separation of garnet (Table 6) show that the magnetic fraction is enriched with garnet, mica and magnetite. At magnetic field 13000 gauss, magnetic fraction about 15 % by weight was obtained with 30.39 % garnet and 89.92 % recovery from a feed containing 16.16 % garnet. It contains about 24.99 % mica and other clay minerals. This magnetic fraction will be further treated with gravity separation to separate garnet from mica and clay minerals due to difference in gravity.

The non-magnetic fraction was about 85 % by weight enriched with feldspar, kaolin and quartz. It could be used in ceramic industry.

Magnetic Separation of Sillimanite and Garnet using "Carpco" Magnetic Separator:

Table (7) represents the results of magnetic separation of sillimanite at different drum speed. It is clear that increasing the speed from 30 to 50 r.p.m leads to decreasing the magnetic fraction. The assay of sillimanite mineral in the non-magnetic fraction decreases with increasing the drum speed. The non-magnetic fraction at 30 r.p.m represents about 83 % by weight with 30 % sillimanite and 100 % recovery. The magnetic fraction was about 17 % and enriched with 30 % almandine and 29 % biotite. The results of magnetic separation of garnet illustrated in table 8 shows that at 30 r.p.m about 36 % by weight in the magnetic fraction was obtained with 31.01 % garnet and 25.4% mica. The recovery percentage of garnet was about 88.17 %.

Magnetic Separation of Sillimanite and Garnet using Rare Earth Three stage Magnetic Separator:

Table (9) shows results of magnetic separation of three stages. It is seen that the most magnetic fraction was removed in the first stage. The magnetic fraction represents about 19 % by weight with 27 % almandine and 23 % biotite. The non-magnetic fraction about 81 % by weight was obtained with 30 % sillimanite and 20 % albite. The further two stage for cleaning the non-magnetic fraction help in separation almandine and biotite. Table (10) shows the results of magnetic separation using the three magnetic units. It is shown that the magnetic fraction represents about 29 % by weight of the whole sample with 7.31 % sillimanite, 28 % almandine and 29 % biotite. About 70 % by weight in the non-magnetic fraction was obtained with 36 % sillimanite and recovery 99 %. This fraction contains sillimanite, albite, and muscovite. It needs further treatment to separate sillimanite.

The results of magnetic separation of the garnet in three separations stage (Table 11) show that the most magnetic fraction was removed also in the first stage. About 40 % by weight in the magnetic fraction was obtained with 30.91 % garnet and 25.02 % mica. The non magnetic fraction represents about 60 % and enriched with feldspar, quartz and kaolin. It could be suitable for ceramic industry. The results of magnetic separation using the three units are illustrated in table 12. About 47.8 % by weight was obtained with

30.33 % garnet, 22.04 % mica and 20 % magnetite. The garnet could be separated from the others using shaking table due to difference in specific gravity. The non magnetic fraction enriched with feldspar, quartz and clay. It could be used in ceramic industry. Figs. (6 and 7) show X-ray diffractograms of sillimanite and garnet after each separation proccess.

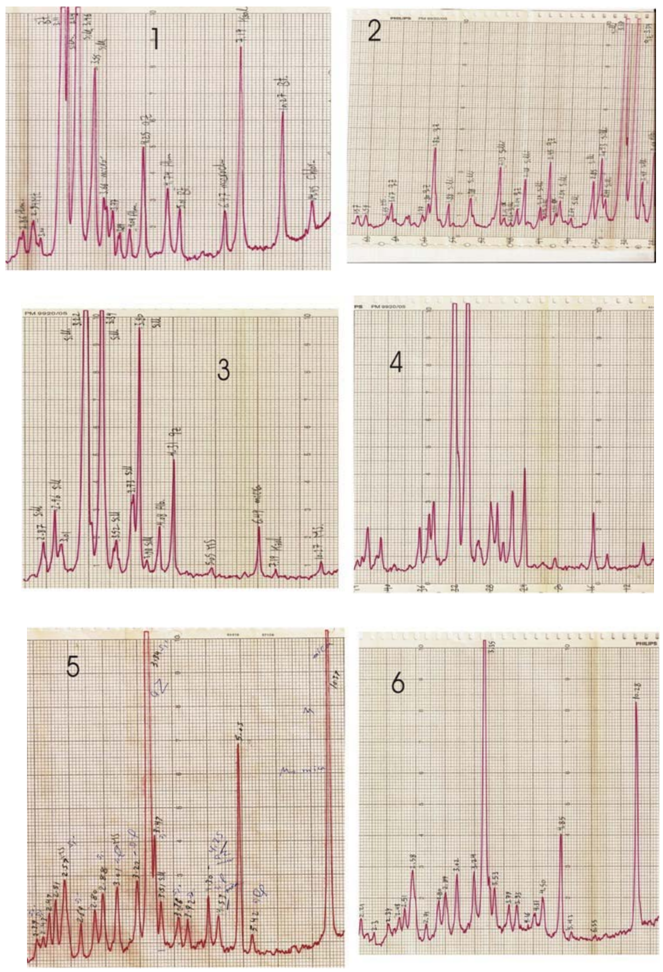

Fig. 6b: The X-ray diffraction pattern of sillimanite.1. The rock, 2. After crushing, 3&4. After magnetic separation, 5. After grinding, 6. After grinding with time.

Table 5: Mineralogical analysis of magnetic separation of sillimanite by using Cross Belt.

Magnetic Field, Gauss	Fraction	Wt. %	Sillimanite	Rec. %	Quarz	Albite	Almandine	Biotite	Muscovite	Corun-dum	Kaoln	K-feldspar
10000	Mag.	1.13	1.7	0.06	3.4	0.01	36.30	30.70	1.2	0.01	0.12	0.21
	Non.	98.87	31.14	99.94	30.5	1.3	0.02	0.02	0.5	0.03	4.32	8.13
	Total	100.0	30.77	100	30.19	1.29	0.43	3.70	0.51	0.03	4.27	8.04
13000	Mag.	2.47	1.02	0.08	2.3	3.6	35.51	31.99	1.1	0.1	0.9	1.2
	Non.	97.53	30.9	99.92	30.4	30.3	0.46	3.42	2.1	0.01	2.12	2.4
	Total	100	30.16	100	29.7	29.7	1.33	4.13	2.08	0.01	2.09	2.37

Table 6: Mineralogical analysis of magnetic separation of garnet by using Cross Belt.

Magnetic Field, Gauss	Fraction	Wt. %	Garnet	Dis. %	Mica	Plagioclase	Quartz	Kaolin	Chlorite	Magnetite	Actinolite	K-feldspar

10000	Mag.	4.68	31.01	84.72	25.11	5.12	4.3	8.3	9.31	11.4	4.13	1.31
	Non.	95.32	5.12	15.28	1.12	29.1	32.9	13.9	1.01	0.31	0.31	16.19
	Total	100.0	17.50	100	1.39	28.0	31.6	13.84	1.40	0.44	0.49	15.49
13000	Mag.	14.96	30.39	89.92	24.99	5.31	3.91	6.47	8.22	13.9	5.14	1.66
	Non.	85.04	3.12	10.08	1.91	28.3	29.9	14.3	2.21	0.48	0.92	18.9
	Total	100	16.16	100	2.17	24.8	26.1	14.11	3.11	0.81	1.55	16.32

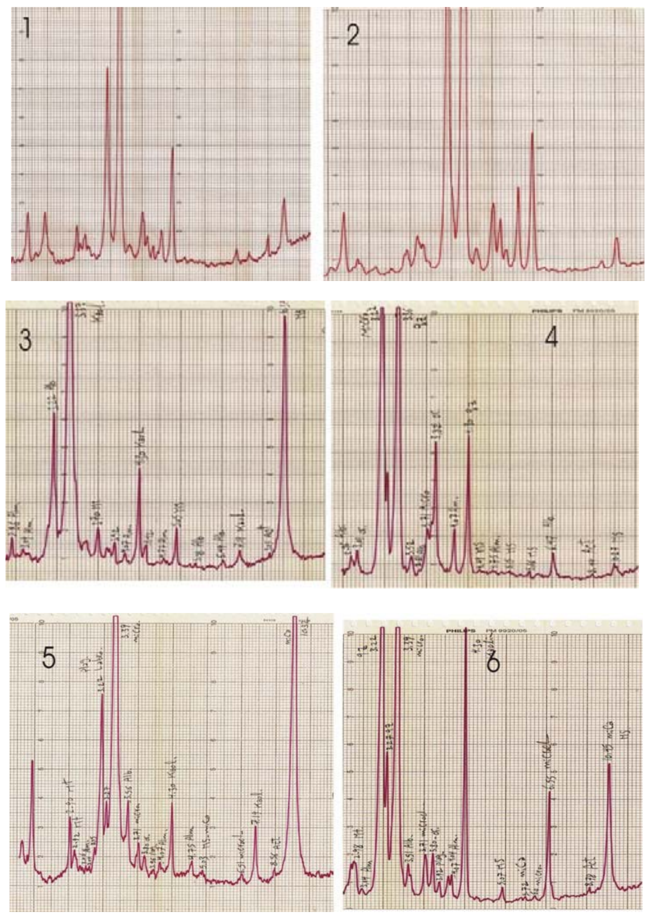

Fig. 7: The X-ray diffraction pattern of garnet

Table 7: Mineralogical analysis of magnetic separation of sillimanite by using Carp co.

Speed	Fraction	Wt.%	Sillimanite	Dis.%	Quartz	albite	Almandine	Biotite	Muscovite	Corundum	Kaolin	K-feldspar
30	Mag.	17.15	0.01	0.01	3.1	0.01	30.1	29.1	2.5	0.02	2.1	0.03
	Non-Mag.	82.85	30.30	99.99	35.7	31.7	0.01	0.02	1.8	0.01	0.3	0.01
	Total	100.0	25.10	100	34.74	26.26	5.17	5.01	1.92	0.01	0.61	0.01
40	Mag.	7.04	2.7	0.66	2.40	0.01	29.91	28.11	2.6	0.01	22.60	0.01
	Non-Mag.	92.96	30.90	99.34	26.4	31.3	0.02	2.7	2.1	0.03	1.2	3.2
	Total	100	28.92	100	24.71	29.1	2.12	4.49	2.14	0.28	1.30	2.11
50	Mag.	4.96	2.7	0.45	3	0.01	30.4	34.1	2.7	0.04	5.29	0.2
	Non-Mag.	95.04	31.1	99.55	34	26.1	0.3	1.2	1.2	0.1	1.10	2.4
	Total	100	29.69	100	32.46	24.80	1.79	2.83	1.27	0.10	1.31	2.29

Table 8: Mineralogical analysis of magnetic separation of garnet by using Carp co.

Speed	Fraction	Wt.%	Garnet	Dis.%	Mica	Plagioclase	Quartz	Kaolin	Chlorite	Magnetite	Actinolite	K-feldspar
30	Mag.	35.72	31.01	88.17	25.4	2.51	4.31	8.79	5.31	15.3	6.31	1.06
	Non.	64.28	3.81	11.83	9.21	18.2	31.9	17.1	1.3	1.2	2.1	15.3

	Total	100.0	16.81	100	12.67	12.6	22.1	15.32	2.73	6.24	3.60	10.21
40	Mag.	23.22	32.3	93.16	25.9	3.91	3.12	5.52	4.41	14.4	7.41	3.03
	Non.	76.78	2.17	6.84	6.12	20.3	33.1	18.7	1.12	1.11	0.97	16.41
	Total	100	16.57	100	8.61	7.72	10.1	17.04	3.65	2.97	5.91	6.14
50	Mag.	14.69	31.9	85.06	24.11	5.21	2.91	12.86	7.31	6.13	8.49	1.09
	Non.	85.31	5.13	14.79	10.1	20.2	29.2	21.1	0.13	0.21	0.98	13.09
	Total	100	17.93	100	12.06	17.9	25.4	19.95	1.18	1.08	2.08	11.33

Table 9: Mineralogical analysis of magnetic separation of sillimanite by using Rare Earth Three stage magnetic Separator.

stage	Fraction	Wt.%	sillimanie	Dis.%	Quartz	Albite	Almandine	Biotie	Muscovite	Corundum	Kaolin	K-feldspar
1	Mag.	18.53	8.97	8.74	11.93	8.91	27.42	23.11	1.15	18.19	0.12	1.11
	Non.	81.47	30..31	91.26	31.25	20.62	0.01	0.001	5.33	0.001	7.31	5.31
	Total	100	26.36	100.00	27.67	18.45	0.091	4.28	4.56	3.37	5.98	4.53
2	Mag.	0.22	3.91	0.05	10.63	9.21	26.98	28.11	1.00	20.13	0.01	0.02
	Non.	81.25	31.44	99.95	30.49	19.90	0.02	0.001	5.01	0.03	9.01	4.109
	Total	81.47	31.37	100.0	30.44	19.87	0.09	0.08	5.00	0.08	8.99	4.10
3	Mag.	0.76	4.01	0.18	6.94	5.39	29.14	29.41	1.42	16.19	1.55	2.01
	Non.	80.49	30.55	99.82	31.31	29.91	0.01	0.02	2.548	0.011	4.331	7.21
	Total	81.25	30.30	100.00	31.08	20.80	0.28	0.29	2.50	0.16	4.31	7.16

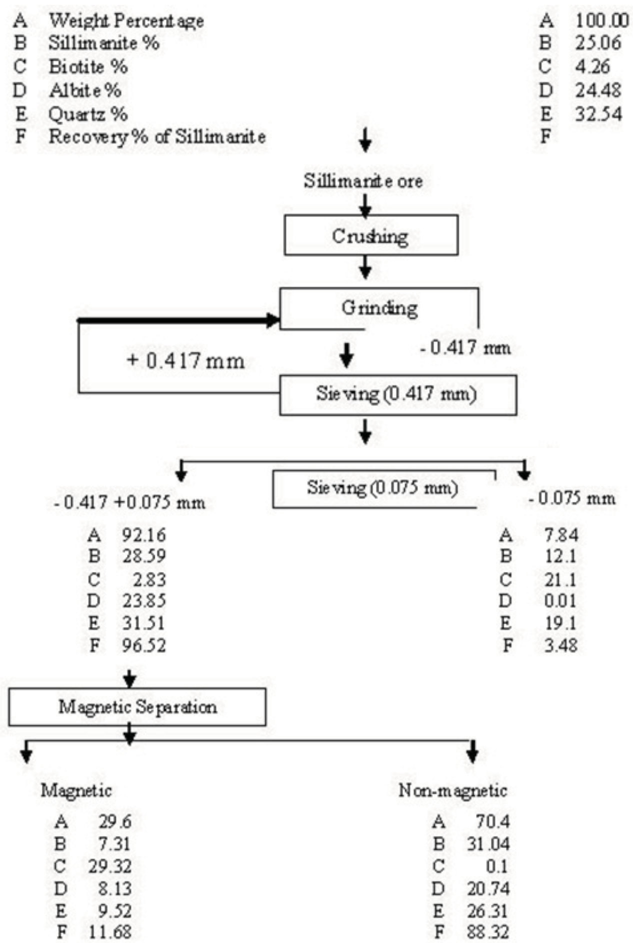

Fig. 8: Fiowsheet of sillimanite ore

Table 10: Mineralogical analysis of magnetic separation of sillimanite by using Rare Earth Three stage magnetic Separator.

Fraction	Wt. %	sillimanite	Dis. %	Quartz	Albite	Almandine	Biotite	Muscovite	Corundum	Kaolin	K-feldspar
Mag.	29.6	7.31	0.23	12.52	8.13	28.60	29.32	0.11	15.30	0.71	0.81

Non.	70.4	36.04	99.77	30.31	29.74	0.01	0.1	1.41	0.011	1.33	1.31
Total	100.0	36.07	100.0	30.21	28.67	0.09	8.00	4.19	4.18	4.30	6.91

Table 11: Mineralogical analysis of magnetic separation of garnet by using Rare Earth Three stage magnetic Separator.

stage	Fraction	Wt.%	Garnet	Dis.%	Mica	Plagioclase	Quartz	Kaolin	Chlorite	Magnetite	Actinolite	K-feldspar
1	Mag.	39.7	30.91	73.32	25.02	4.36	2.39	8.34	2.14	19.39	2.42	5.03
	Non.	60.3	10.13	26.66	13.44	30.41	29.31	6.91	4.18	1.81	1.41	2.4
	Total	100	20.06	100	18.98	20.07	18.62	7.59	3.37	10.21	1.81	3.44
2	Mag.	3.44	31.89	79.70	21.31	4.91	2.74	5.12	1.91	18.40	3.81	4.89
	Non.	56.86	7.44	20.30	16.11	25.46	29.11	8.81	4.41	1.33	3.42	3.91
	Total	60.3	19.13	100	16.76	22.87	16.20	8.60	3.22	2.30	3.44	3.97
3	Mag.	1.69	30.02	79.40	23.4	3.72	1.33	6.41	2.13	18.13	8.22	4.48
	Non.	55.17	7.13	20.60	12.9	30.19	32.91	3.91	5.81	1.11	2.03	4.01
	Total	56.86	18.07	100	14.37	26.49	17.81	3.98	4.05	9.25	2.21	4.02

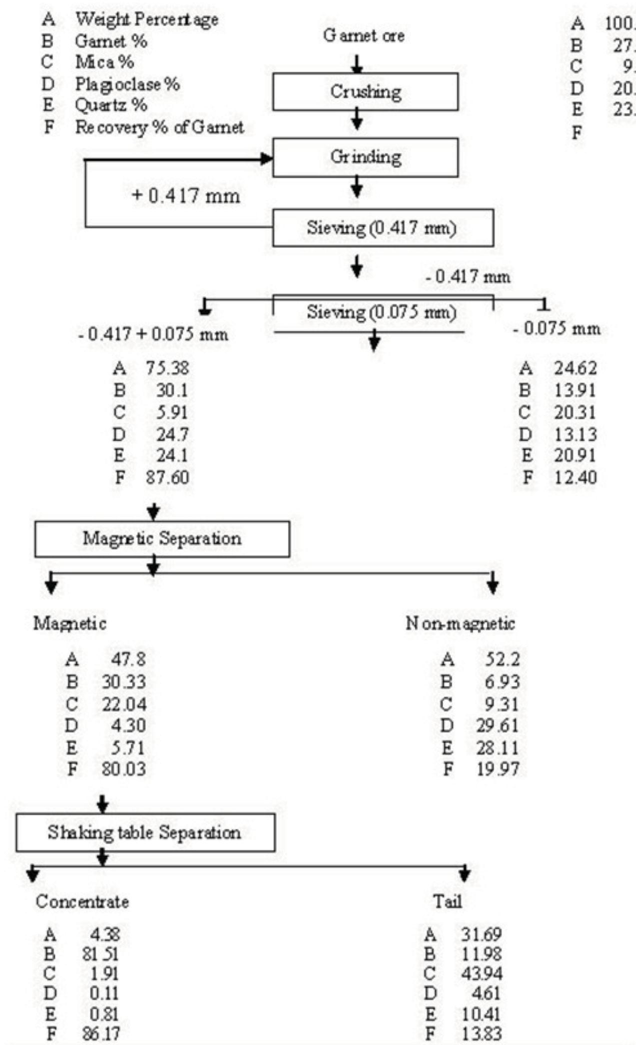

Fig. 9: Fiowsheet of gamet ore material.

Table 12: Mineralogical analysis of magnetic separation of fraction (-0.417+0.075 mm) by using Rare Earth Three stage magnetic Separator.

Fraction	Wt.%	Garnet	Dis.%	Mica	Plagioclase	Quartz	Kaolin	Chlorite	Magnetite	Actinolite	K-feldspar

Mag.	47.8	30.33	71.76	22.04	4.30	5.71	5.12	6.13	19.81	4.09	2.51
Non.	52.2	6.93	15.83	9.31	29.61	28.11	2.10	3.91	1.10	2.02	16.91
Total	100	18.12	87.60	15.39	17.51	17.40	3.54	4.97	10.04	3.01	10.03

Table 13: Mineralogical analysis of gravity separation of Magnetic fraction using shaking table.

Fraction	Wt.%	Garnet	Dis.%	Mica	Plagioclase	Quartz	Kaolin	Chlorite	Magnetite	Actinolite	K-feldspar
Conc.	4.38	81.51	86.17	1.91	0.11	0.81	1.05	0.11	14.81	0.01	0.03
Tail	31.69	11.98	13.83	43.94	4.61	10.41	9.0	6.71	3.91	2.11	7.33
Total	36.07	45.22	100	23.85	2.46	5.82	5.20	3.56	9.12	1.11	3.84

Table 14: The chemical analyses of standard sillimanite and the upgraded Hafafit sillimanite.

Oxides	Standard sillimanite	Upgraded Hafafit sillimanite
Al_2O_3	40-43 %	32-37 %
SiO_2	48-51 %	55-58 %
Fe_2O_3	1.69-5.59 %	0.1-1.03 %

Source of standard sillimanite: Institute of Developing Economies (Business Matching).

Gravity Separation of the Magnetic Fraction of Garnet:

The results of the shaking table of the magnetic fraction (Table 13) shows that it is possible to separate two fractions one enriched with garnet and the other enriched with mica and clay. About 4 % by weight in the concentrate was obtained with 81.51 % garnet and 86.17 % recovery.

The tail fraction represents about 32 % with 43.94 % mica. It needs further treatment using flotation technique to separate mica.

The suggested flowsheets for up-grading of sillimanite and garnet bearing schist are given in Fig. 8 & 9.

World Market Characteristics for Using Sillimanite Refractory Material:

Product available in size (-0.417+0.075 mm) or aggregates to customer species. Chemical analysis of both standard sillimanite material and the upgraded Hafafit sillimanite are listed in Table (14). From table (14), the upgraded sillimanite still shows lower Al_2O_3 (32-37 %) and high SiO_2 (55-58 %) compared to the standard sillimanite (40-43 % Al_2O_3 and 48-51 % SiO_2). Consequently more studies to separate kyanite for upgrading the Hafafit sillimanite material to match with the standard material used in industry are recommended.

Conclusions:

- The applied beneficiation and processing methods given in the 2 sheets succeeded upgrading sillimanite in which Al_2O_3 content 32 -37 %.
- The non-magnetic fractions (about 85 wt. %) enriched with feldspar, kaolin and quartz could be used in ceramic industry.
- Upgrading kyanite of these schists is recommended to obtain sillimanite material in which Al_2O_3 content approach to the standard are needed for the sillimanite refractory material.
- The applied two flow sheets achieved separation of upgraded sillimanite and garnet.

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