

## SIDERITE ORE PHYSICAL SEPARATION AND REVERSE FLOTATION

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(Received 17 February 2012; Accepted 27 June 2012)

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### Abstract

The Kremikovci deposit of siderite ore is localized at 15 km NE from Sofia town (Bulgaria). The running characteristics of siderite ores are investigated by complex methods of research. The siderite ore mineral composition dominates by siderite, barite and quartz. Microscopic polished sections have been studied to assess the size of liberation. Crushing and grinding tests have been established to achieve the assessed liberation size. Separation on a spiral concentrator, after grinding has been performed. The separation tests have been carried out with raw and calcined siderite ore. A high iron recovery has been achieved. Second series of tests were performed with "Jones" type wet high intensity magnetic separator. The laboratory test run as follow: after grinding the raw ore has been calcinated, followed by low and high intensity magnetic separation. After calcination an enrichment in a low intensity magnetic separator gave high iron content, compared to the wet high intensity magnetic separation, but the quartz content in the magnetic product occurred. Concerning the different electrostatic properties of the siderite and the gangue minerals, raw siderite ore has been also tested in electrostatic separator. Finally amine flotation tests of raw and calcined ore have been carried out. On the basis of the laboratory results siderite ore beneficiation method has been analyzed.

**Key words:** gravity, magnetic and electrostatic separation, siderite ores.

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### 1. Introduction

In the practice of beneficiation of iron ores magnetic, gravity separation and reverse flotation are widely used, but the fine interlocked quartz particles in most cases remain in the concentrate. The maximum iron content obtained from the Kremikovtzi deposit of the non-calcined siderite concentrates theoretically is 48% Fe, together with Mn, Ca and Mg, because they are in the crystal structure of the

mineral. This fact makes beneficiation of siderite ores very difficult task.

Iron content ratio to manganese in siderite is close to Fe:Mn~4:1 [1]. After heating at 650°C [2] as a result of decarbonatization ferromagnetic minerals like magnetite, maghemite and Mg-jacobsite are formed and also paramagnetic like hematite - usually along the surface of the ore pieces where the oxidation process is more intensive.

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The gravity separation of iron ores is a common practice because of the low costs and environmentally friendly process [3]. Due to the difference in specific gravity between siderite and quartz a reasonable upgrading could be obtained by spiral separator which is an object of the present study. The practice has shown that difference higher than 0.5 SG is required for acceptable separation to be achieved [4].

The choice of beneficiation methods mostly depends on the grain size of the sample which ultimately is based on the liberation of iron-bearing minerals from the gangue.

The gravity and magnetic methods are restricted to coarse grain size particles and these methods have their own limitations when the particle size is fine such as in iron ore slimes [5]. When the test sample contains relatively lesser gangue, it is easier to float it and hence reverse flotation can be employed rather than direct flotation where in major proportion of the material, otherwise, would have to be floated. As such, the reverse flotation is the usual process for the beneficiation of iron ore slimes. Amines are the only

cationic collectors used by industries in reverse flotation of iron ores. It is very common to upgrade iron ore by reverse flotation, because it usually has a high iron-grade and only the minor impurities such as the silicates are being floated.

Wet high intensity magnetic separation is mostly used method for enrichment of iron ores. Method for separation is based on different magnetic susceptibilities of iron and manganese minerals from other contaminants in the ore. Electrostatic separation is selective sorting of solid species by means of utilizing forces acting on charged or polarized bodies in an electric field. Electrostatic separation is important in the production of minerals, and separation of other valuable materials. The effectiveness of the separation primarily relies on the ability to control particle tribocharging.

## 2. Materials and Methods

Representative siderite ore sample from Kremikovci deposit were characterized. Chemical composition of the raw siderite ore is presented in Table 1.

**Table 1.** ICP analyses of raw siderite ore, %

Product	Al <sub>2</sub> O <sub>3</sub>	CaO	Fe <sub>2</sub> O <sub>3</sub>	K <sub>2</sub> O	Na <sub>2</sub> O	P <sub>2</sub> O <sub>5</sub>	SO <sub>3</sub>	SiO <sub>2</sub>	MgO	MnO	TiO <sub>2</sub>	BaO	LOI
Siderite ore	0.87	3.23	37.74	0.12	0.04	0.01	1.92	13.3	5.05	7.48	0.06	3.81	25.6

Size reduction has been performed on laboratory jaw crusher with largest compression resistance of the material 320 Mpa. Second stage of size reduction has been performed on roll crusher.

Lab crusher used in the experiments comprised by two hardened alloy steel rollers with 100 mm faces and 250 mm diameters. The rollers are fitted to a steel shaft and are mounted on heavy duty gunmetal bearings.

The outside bearings are provided with heavy duty compression springs, which help in increasing the space between the rolls, when a piece of material cannot be crushed. Square threaded bolts are provided to adjust the gap between the rolls. The drive was by a heavy duty motor, through V- belts to a set of gears and further to the rollers. A hopper has been provided for feeding material. The whole arrangement is mounted on a steel frame.

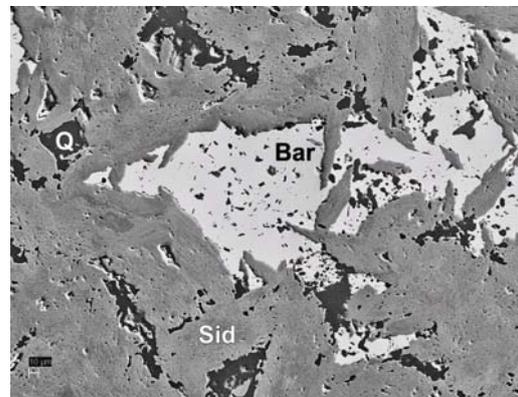
Grinding in lab ball mill followed the two stages of crushing. The grinding time and the particle size distribution have been examined for achievement of the liberation size of the minerals. The ball mill used in this study has been of a 3.3 dm<sup>3</sup> volume and the mass of grinding bodies of 5 kg [6].

## 2.1. Mineralogical studies

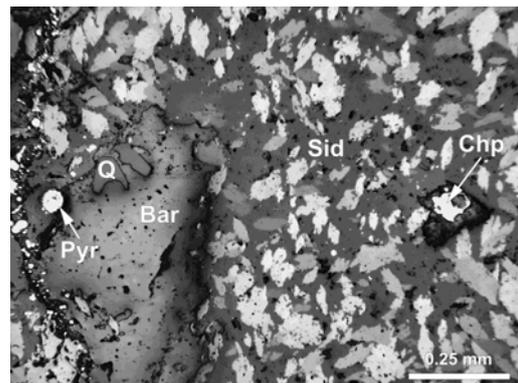
As the fragmented state of material did not allow detailed macroscopic examination of the sample, more emphasis was placed on laboratory techniques. For the mineralogical analysis an optical microscope has been used. Characterization of siderite ore has been performed on scanning electronic microscope Meiji MT 9900 for reflected and transmitted light. Several average sample taken from grinded down to “- 0.063 mm” siderite ore have been analyzed.

The mineral siderite is generally typical for carbonate rocks, fine-grained to medium-grained, occasionally coarse - grained. Quartz in siderite ores cements the siderite grains and aggregates and is well shaped with isometric habit, variety of microquartz.

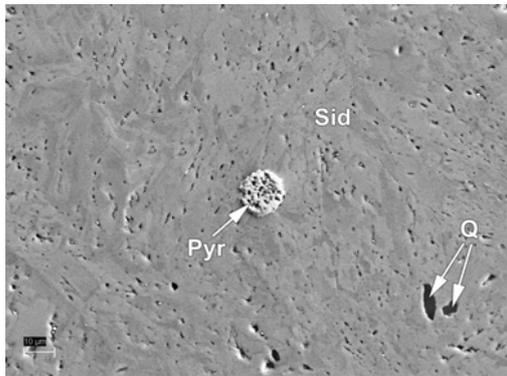
The primary siderite grain sizes are generally 0.05-0.25 mm while the same for recrystallized are from 0.3-0.5 mm to 2-3 mm. Quartz grains in the siderite ores with variety of microquartz shows grain size up to 0.01 mm, in barite-sulfide nests and veinlets – up to 0.5 mm. Liberation size has been defined after microscopic pictures of siderite polished sections in both transmission and reflected light (Fig.1 to 7).



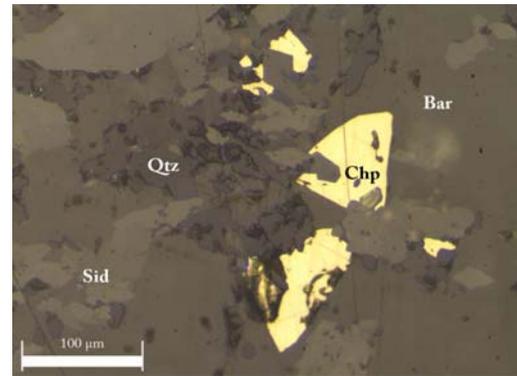
**Figure 1.** Massive siderite (Sid) with chalcopyrite (Chp), barite (Bar), microquartz (Q) and framboidal pyrite (Pyr)



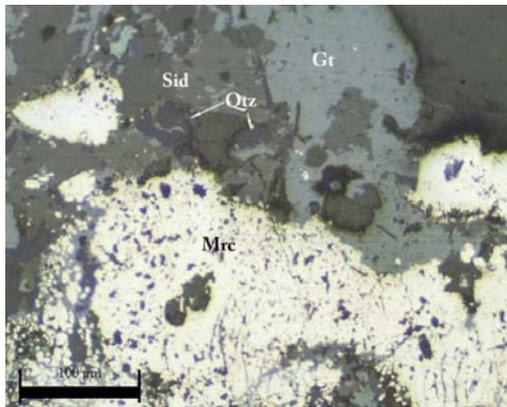
**Figure 2.** Barite (Bar) nest in massive siderite (Sid) with microquartz (Q) cementing the carbonate grains (SEM-BSE, Krem10)



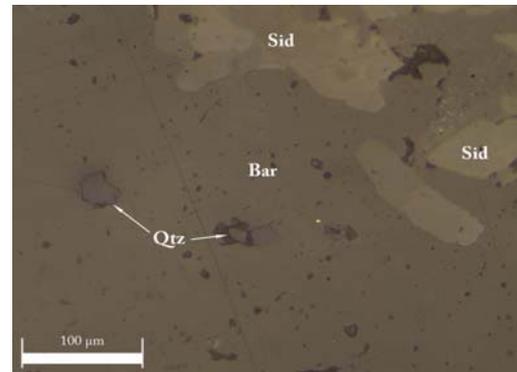
**Figure 3.** Massive siderite (Sid) with microquartz (Q) cement in interstices and framboidal pyrite (Pyr), (SEM-BSE, Krem12)



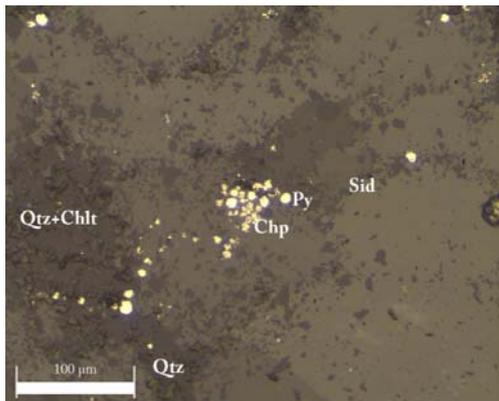
**Figure 6.** Massive siderite (Sid) with quartz (Q) and barite (Bar). Chalcopyrite (Chp) grains



**Figure 4.** Massive siderite (Sid) with quartz (Qtz) cement in interstices and goethite (Gt)



**Figure 7.** Massive siderite (Sid) with microquartz (Q) in barite (Bar) veins



**Figure 5.** Massive siderite (Sid) with quartz (Q) and Quartz+Chlorite minerals and framboidal pyrite (Py)

Based on the method of statistical observation from mineralogical study optimal liberation size has been achieved: for the quartz the main mass is between 30 – 60 μm; for barite between 80-100 μm and for the other gangue minerals between 60 and 100 μm. Consequently, the main mass after grinding should be between 30 and 100 μm.

## 2.2. “Jones” type Magnetic Separator

“Jones” type magnetic separator has been used for magnetic separation exami-

nations. The design of this type of magnetic separator has been based around a rotating annulus or carousel containing a magnetic matrix. As the matrix passes through a high intensity magnetic circuit, a high intensity magnetic field and gradient are induced into the matrix.

The feed passes vertically through the induced matrix section, the last capturing magnetic particles.

Figure 8 shows a wet laboratory magnetic separator designed by Jones. The steel balls in the plastic compartment placed between the separator magnetic poles create a gradient of magnetic field as well as provide surface for collection of magnetic particles.

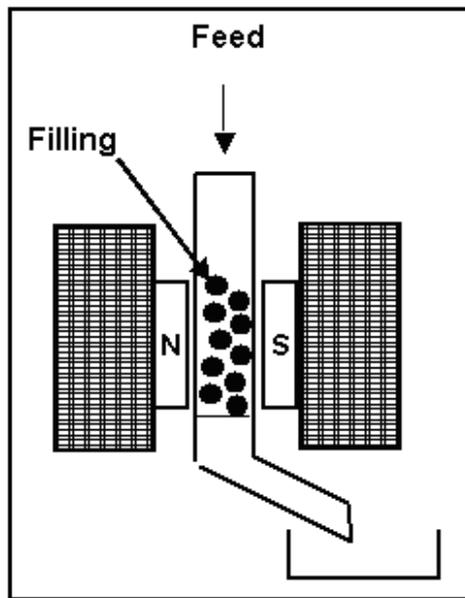


Figure 8. Laboratory Jones magnetic separator

Finely ground material is delivered from the top as an aqueous suspension. Particles with a high magnetic susceptibility are attached to the steel balls during the suspension flow through the

separator while the weakly magnetic and diamagnetic particles are transported with water to the container beneath the separator (cycle 1, Fig. 9). Next, the electromagnets of the separator are turned off, the compartment with the balls is rinsed with water, and the magnetic particles are recovered in another container placed beneath of the separator (cycle 2, Fig. 9). Flowsheet of the experiments with LIMS and WHIMS is presented on Fig.10.

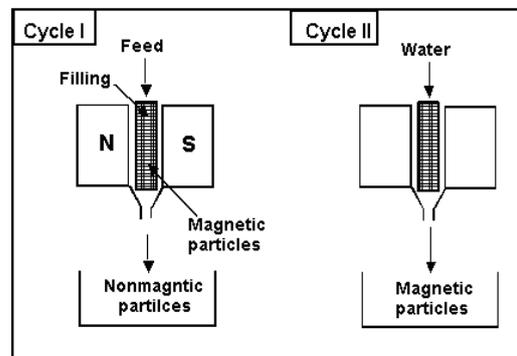


Figure 9. Separation in a Jones magnetic separator

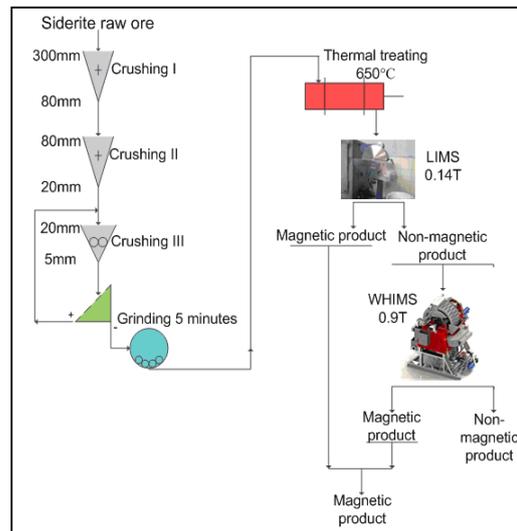


Figure 10. Flowsheet of LIMS and WHIMS experiment

### 2.3. High Tension Electrostatic Separator

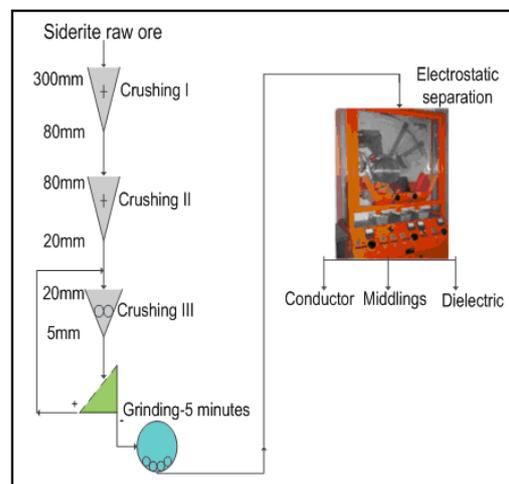
Laboratory High Tension Electrostatic Separator has been used for separation of silica from iron minerals, due to their different properties. Separation of silica from iron minerals due to their electrical properties is presented on table 4.

Laboratory unit utilizing the combination pinning/lifting effects of high tension and electrostatic charges for the separation of conductive and non-conductive materials.

The High Tension Laboratory Electrostatic Separator can handle products in a size range from 8 to 250 mesh. Larger particles can be tested with some modification to the equipment. Typical feed capacities range from 9.2 to 36.4 kg per hour per cm of the roll width. The physical design of the machine is such that data gained through testing can be directly projected for sizing of production equipment. Flow of material from the hopper can be regulated by an adjustable gate. The vibratory feeder positioned under the hopper discharge is adjustable.

The feed rate is precisely controlled by a simple AC autotransformer single phase 115 V 60 Hz controller. Feed control ranges from 0 to 100% (from a few grains of product per second to the maximum). A brush is mounted at the nine o'clock position around the drum surface to remove any particles which may remain. Positions of the electrodes, both angular and distance, can be repeatably selected or returned to by reference to polar coordinates on a positioning panel.

Flowsheet of the experiments provided with electrostatic separation is presented in figure 11.



**Figure 11.** Flowsheet of the treatment with electrostatic separation

### 2.4. Laboratory spiral separator

Laboratory spiral separator could separate minerals accordingly to the different specific gravity and their relative movement in response to gravity, centrifugal force and other forces in the fluid medium [7].

The laboratory model spiral is a three-turn, wear-resistant stainless steel construction helix designed for concentrating iron ores with less than 20% light mineral content. Spiral is connected to a slurry buffer and pump which agitate slurry before entering the helix. Flowrate of the slurry in experiments has been adjusted to 388 dm<sup>3</sup>/h and solid-liquid ratio as 1:3 [8]. Gravity separation flowsheet is presented of figure 12.

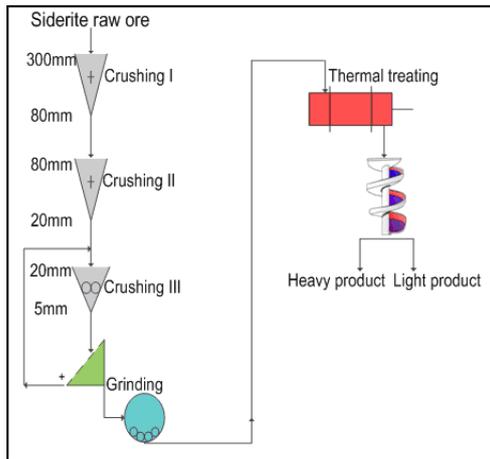


Figure 12. Gravity separation flowsheet



Figure 13. Laboratory spiral concentrator

## 2.5. Flotation

Laboratory flotation cell has been used in experiments. Its characteristics as follow:

- Removable cells of the volume 0.5 dm<sup>3</sup> for the rougher flotation and 0.3 dm<sup>3</sup> for the two cleaner flotation.

- Fine adjustment of air flows within the cell.
- Motor of 0.37kW, dc, 90/130 VAC allowing connection to 110V-240 V, 50/60 Hz, 10 A single phase socket outlet.



Figure 14. Raw siderite ore amine flotation

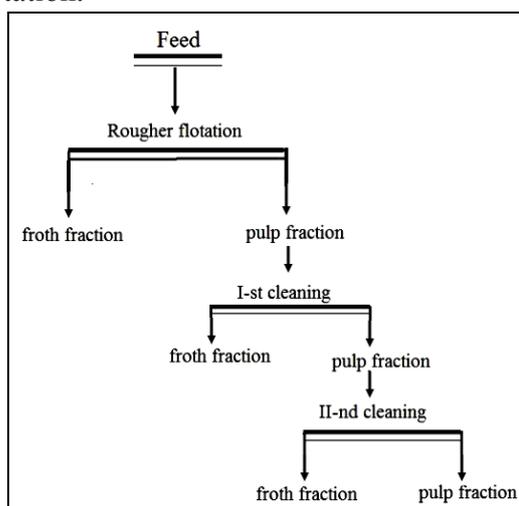


Figure 15. Calcined siderite ore amine flotation

## 2.6. Laboratory flotation tests

Reverse flotation of silica minerals is the most widespread method for treatment of the iron ores worldwide. During the process the gangue is separated into float fraction and the valuable iron minerals – into the iron concentrate (pulp fraction).

Flotation experiments have been provided on raw and calcined siderite ore. First experiment was provided on raw siderite ore in following conditions. Float fraction (silica product) from the rougher flotation has been separated and added to concentrate after first and second cleaning flotation.



**Figure 16.** Flotation test flowsheet

As previously referred in the process of reverse flotation the gangue is separated into float fraction (*silica product*) and the valuable iron minerals – into the pulp fraction (*iron product*). The following conditions have been insured:

- Rougher flotation: Solid: liquid ratio – 1:3, 150 g/ton collector: Lilaflo 811M, pH = 8, agitation time 2 min, flotation time: 5 min; 0.5 dm<sup>3</sup> cell volume;

- First cleaner flotation and Second cleaner flotation: Flotation time: 2 min; collector: 100 g/ton Lilaflo 811M, 1 min agitation time; 0.3 dm<sup>3</sup> cell volume.

Thermal treatment and new highly magnetic mineral formation has been performed in muffle furnace with following technical characteristics: A heating range from up to 1200°C; Heating space volume: 6 dm<sup>3</sup>; Alternative electronic single set point control or programmable control; Temperature range: Ambient to 1150 °C; el. supply: 230 V, 50 Hz, single phase; Heating ratio 10°C/min.

## 3. Results and Discussion

### 3.1. Wet high intensity magnetic separation experiments (WHIMS)

After grinding on three stages and thermal treatment of the siderite ore to 650°C, next operation has been low intensity magnetic separation on already calcined siderite ore.

After calcination high magnetic minerals like maghemite and magnetite has been observed which are easily recovered in concentrate with LIMS (Low intensity magnetic separation).

Laboratory test has been done on laboratory magnetic separator SALA with intensity of the field B=0.14T. Non magnetic product from LIMS has been fed to WHIMS with intensity of the field 0.9T. Laboratory WHIMS used in the experiment was “Jones” type with 2.8 mm gap. Solid liquid ratio was 1:3. Magnetic products from two separators were combined and analyzed. Results from experiments are presented in Table 2.

**Table 2.** Recovery of Fe after LIMS;  $B = 0,14T$ ;  $650^{\circ}C$ 

Product	Fe, %	Yield, %	Recovery, %
Feed	32.5	100.00	100.00
Concentrate	45.6	54.15	75.9
Tailings	17.1	45.85	24.1

Recovery of iron after LIMS was received 75.9% due to newly produced minerals with high magnetic properties after thermal treatment of the ore. Non magnetic product from LIMS was fed to WHIMS "Jones" type with intensity of the field  $B = 0.9T$ . Recovery of iron in magnetic fraction was 81.1%. Results are presented in Table 3.

**Table 3.** Recovery of Fe after WHIMS;  $B = 0.9T$ 

Product	Fe, %	Yield, %	Recovery, %
Feed	17.1	100.00	100.00
Concentrate	47.5	15.22	42.9
Tailings	11.5	84.78	57.1

Recovery achieved after both magnetic separations was 81.1% with Fe content of 45.8%. Iron content in tailings was 16.8%. In tailings from magnetic separation main mineral is barite which could be recovered with barite flotation, gravity or electrostatic separation. Other gangue minerals observed in tailings are quartz, dolomite and calcite.

### 3.2. Electrostatic separation studies

After crushing and grinding to liberation size raw siderite ore was fed to laboratory electrostatic separator. Conditions for electrostatic separation experi-

ment have been following: current on upper electrode - 15000 V and current on lower electrode - 10000 V.

The material was fed to the very thin layer with low speed. Produced were three products:

**Table 4.** Recovery of Fe after Electrostatic separation

Product	Fe, %	Yield, %	Recovery, %
Raw ore	23.20	100	100
Conductor	22.96	65.5	64.8
Middlings	25.08	19.6	21.2
Dielectric	25.15	12.9	14.0

According received results we can conclude that the electrostatic separation is not most appropriate method for separation of iron from contaminants in siderite ores from Kremikovci deposit.

### 3.3. Gravity separation

A representative sample of siderite ore about 400 kg was taken from horizons 472 and 460 m from Kremikovci deposit. The sample is crushed at three stages down to P98 -5 mm. The primary and secondary crushing was performed in jaw crusher and third stage on roll crusher. The first test is carried out with calcinations at  $650^{\circ}C$  of the ground siderite sample. The siderite sample after the third stage of crushing shows the particle size distribution presented on figure 17.

By the aid of riffle divider from the crushed ore were taken two representative samples for the comparative tests with and without calcination. During the process of decarbonisation at  $650^{\circ}C$ , because of the free access of air the crystal lattice of

siderite is transformed into hematite by reaction:  $2\text{FeCO}_3 + 2\text{O}_2 = \text{Fe}_2\text{O}_3 + 2\text{CO}_2$

The restructuring of siderite in hematite as usual generate slimes which reflect upon the recovery of iron in the concentrate and an important aspect of the present study is to establish the impact of this phenomenon on beneficiation efficiency of Kremikovci siderite ore.

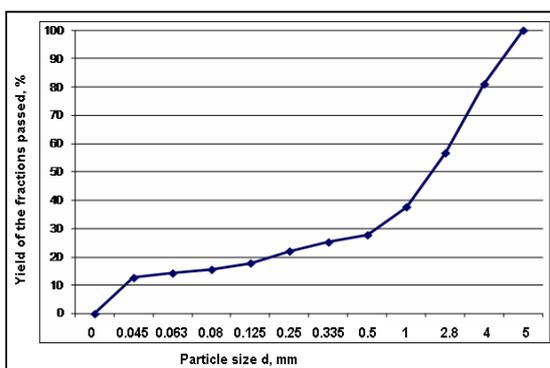


Figure 17. Particle size distribution of the sample after crushing

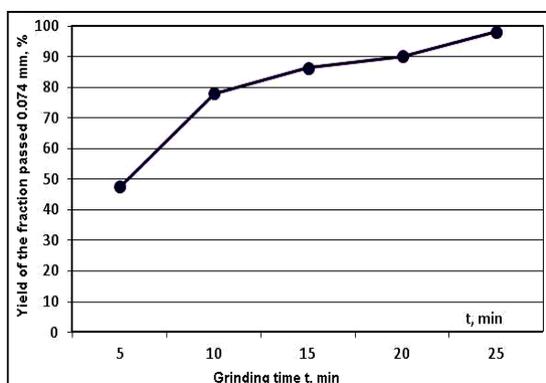


Figure 18. Yield of the fraction “-0.074 mm” as a function of grinding time

The curve of grinding is determined at duration of the process 5, 10, 15, 20 and 25 minutes. The ball charge takes 40 % of the mill volume and a weight of 5 kg.

The ratio solid/liquid has been kept 1:1 and for each test the mill is charged with 330 g siderite ore and 330 ml tap water.

The next step in this study after comminuting the sample is to determine the grinding duration which will be able to ensure a maximum yield of class “-100+30”  $\mu\text{m}$ . The size distribution after each grinding time is determined by laser particle sizer FRITCH Analizete 2020, Germany. The values of yield of this class ( $M_d$ ) for each curve are calculated by the formula (1). The results of these calculations are presented at table 5.

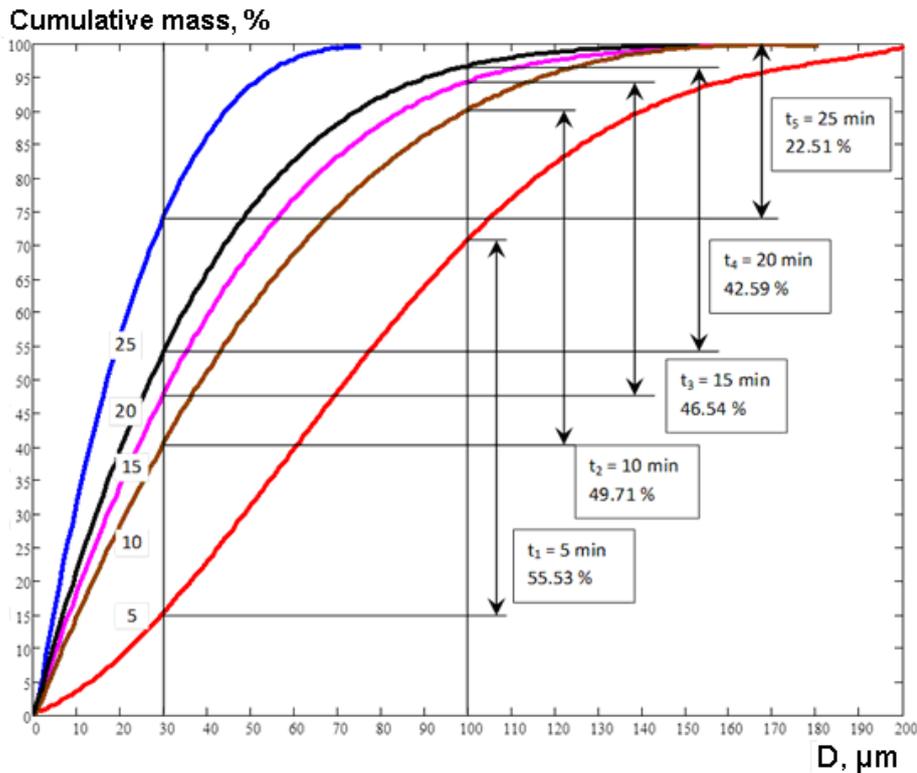
$$M_d := \sum_{i=0}^{100} M_{100} - \sum_{i=0}^{30} M_{30} \quad (1)$$

Table 5. Cumulative mass in the points of 30 and 100  $\mu\text{m}$  for tested grinding times and content of class “-100+30”  $\mu\text{m}$

Time, min	D 100 $\mu\text{m}$ , %	D 30 $\mu\text{m}$ , %	Class “-100+30” $\mu\text{m}$ , %
5	70.82	15.29	55.53
10	90.20	40.49	49.71
15	94.40	47.86	46.54
20	96.73	54.14	42.59
25	96.64	74.14	22.51

The data from the laser particle sizer is visualized on a line scale and the quantities of class “-100+30”  $\mu\text{m}$  are also displayed at Figure 19.

The quantity of classes  $M_d$  decrease with increase of grinding time. At the chart could be seen that it gradually falls down from 55.53 % to 22.51 % and respectively the shortest time is most appropriate.



**Figure 19.** Yield of fraction “-100+30” µm after grinding times of 5, 10, 15, 20 and 25 min.

As usual about 60.0% of the costs in beneficiation are in grinding and the finer grinding except the higher costs will produce a higher quantity of slimes which are not amenable to beneficiation and represent a problem for dewatering and storage.

The test is carried out with the siderite sample crushed in three stages as shown at Fig. 12 and ground for 5 min in a ball mill. The sample was dried in oven at 105°C and then heated in muffle furnace to 650°C for decarbonisation of siderite. The next procedure is to cool it down to room temperature for 5 hours and after that are taken 250 g for separation in laboratory spiral concentrator which is

shown at Figure 13. The results of this test on gravity separation are displayed at Tables 6 and 7.

Taking into consideration the stoichiometric ratio between iron and Fe<sub>2</sub>O<sub>3</sub> of 0.6994 it could be calculated its recovery in respective products which is displayed for calcined sample are shown in Table 7.

The next test is targeted to demonstrate where is the best position of calcinations process before or after gravity separation. For this purpose is taken representative part of the crushed sample and was ground also for 5 min at the conditions described above.

**Table 6.** Assays for gravity separation after calcinations

Product	Al <sub>2</sub> O <sub>3</sub>	CaO	Fe <sub>2</sub> O <sub>3</sub>	K <sub>2</sub> O	Na <sub>2</sub> O	P <sub>2</sub> O <sub>5</sub>	SO <sub>3</sub>	SiO <sub>2</sub>	MgO	MnO	TiO <sub>2</sub>	BaO	LOI
Feed	1.17	3.82	46.48	0.33	0.34	0.01	6.63	19.79	6.30	9.43	0.05	2.35	2.68
Heavy	0.86	3.58	55.23	0.18	0.04	0.01	3.05	5.24	6.51	9.75	0.11	9.28	5.30
Light	2.0	3.58	23.7	0.34	0.69	0.01	1.19	40.49	7.75	9.68	0.05	1.19	4.90

**Table 7.** Recovery of Fe of the calcined sample

Product	Fe, %	Yield, %	Recovery, %
Feed	32.04	100.00	100.00
Concentrate	38.63	70.0	84.46
Tailings	16.6	30.0	15.54

The results obtained of separation are analyzed and displayed at Tables 8 and 9.

The finer heavy minerals have lower forces acting upon them and therefore tend to stay closer to the inner wall, the coarser particles have the greater forces

and travel outward toward the outer region of the spiral. Refractory heavy minerals (clay minerals "ilite, montmorillonite") are difficult to be removed, as they tend to be coarser and have specific gravities much closer to quartz minerals.

**Table 8.** Assays for gravity separation before calcinations

Product	Al <sub>2</sub> O <sub>3</sub>	CaO	Fe <sub>2</sub> O <sub>3</sub>	K <sub>2</sub> O	Na <sub>2</sub> O	P <sub>2</sub> O <sub>5</sub>	SO <sub>3</sub>	SiO <sub>2</sub>	MgO	MnO	TiO <sub>2</sub>	BaO	LOI
Feed	0.87	3.23	37.74	0.12	0.04	0.01	1.92	13.30	5.05	7.48	0.06	3.81	25.61
Heavy	0.15	3.51	43.20	0.08	0.04	0.01	1.67	3.96	5.10	7.40	0.07	4.20	26.23
Light	2.63	1.48	11.18	0.20	0.04	0.01	2.04	35.49	3.40	5.46	0.01	1.58	25.20

**Table 9.** Recovery of Fe after gravity separation before calcinations

Product	Fe, %	Yield, %	Recovery, %
Feed	22.41	100.00	100.00
Concentrate	30.22	65.15	87.84
Tailings	7.82	34.85	12.16

Typically, spirals alone do not produce acceptable results unless the ore is pre-classified prior to the gravity separation. A narrow particle size range will increase the removal efficiency.

The primary flow is essentially the slurry flowing down the spiral trough under the force of gravity. The secondary flow pattern is radial across the trough. Here, the upper, more fluid layers, comprised of higher density particles, move away from the center while the

lower, more concentrated layers of higher density particles move towards the center.

A spiral will normally achieve a 3:1 upgrading ratio (ratio between head feed grade of heavy minerals and concentrate grade). Therefore, as with most gravity concentrators, a multi-pass flowsheet is generally required to achieve a desired grade and recovery of minerals. According microscopy was defined liberation size of gangue minerals (quartz, dolomite, calcite and clay minerals) to P98 -100  $\mu$ m.

Grinding time in ball mill for 5 minutes and solid liquid ratio 1:1 gives required liberation size of siderite from the most of the gangues minerals. Achieved results for recovery of iron minerals in heavy fraction in test 2, gives a good option to be used spirals for gravity separation of siderite. Except the quartz in tailings are presented as well clay minerals, dolomite and calcite.

### 3.1. Flotation studies

As previously referred in the process of reverse flotation the gangue is separated

into float fraction and the valuable iron minerals - into the pulp fraction.

Flotation experiments have been provided on raw and calcined siderite ore. The first test has been provided on raw siderite ore in following conditions: Solid: liquid ratio - 1:3, 150 g/ton collector Lilafлот 811M, pH = 8, agitation time 2 min, flotation time: rougher flotation – 5 min; I-st cleaner flotation – 2 min, (100 g/ton Lilafлот 811M, 1 min agitation time), II-nd cleaner flotation – 2 min, (100 g/ton Lilafлот 811M, 1 min agitation time),

The results of the flotation experiments are presented in Tables 10 to 12. Following results have been received:

**Table 10.** Raw siderite ore, float fraction and pulp fraction chemical composition

Product	Al <sub>2</sub> O <sub>3</sub>	CaO	Fe <sub>2</sub> O <sub>3</sub>	K <sub>2</sub> O	Na <sub>2</sub> O	P <sub>2</sub> O <sub>5</sub>	SO <sub>3</sub>	SiO <sub>2</sub>	MgO	MnO	TiO <sub>2</sub>	BaO	LOI
Feed	0.87	3.23	37.7	0.12	0.04	0.01	1.92	13.3	5.05	7.48	0.06	3.81	25.6
Float fraction	1.25	1.4	7.65	0.1	0.02	0.01	0.25	71.6	1.8	2.14	0.03	0.6	9.2
Iron product	0.80	3.55	43.1	0.12	0.04	0.01	2.21	3.41	5.62	8.42	0.07	4.38	24.8

**Table 11.** Recovery of iron in the flotation process

Product	Fe, %	Yield, %	Recovery, %
Feed	26.4	100.00	100.00
Float fraction	5.35	15.00	3.1
Iron product	30.14	85.00	96.9

**Table 12.** Recovery of SiO<sub>2</sub> after flotation

Product	SiO <sub>2</sub> , %	Yield, %	Recovery, %
Feed	13.3	100.00	100.00
Float fraction	71.6	15.00	78.97
Iron product	3.41	85.00	21.03

After reverse flotation of raw siderite ore have been achieved recovery of iron in iron product ~97% and ~79% recovery of silica in float fraction. Same conditions for flotation experiments were used on

calcined at 650°C siderite ore. Sample was agitated for 2 minutes with reagent collector Lilafлот 811M. For the rougher flotation time has been 5 min, and for the two cleaning operations - 2 min each. pH

of the solution was adjusted to 8. Float fraction was collected and analyzed. Also iron product and feed material have been

analyzed. Results of the experiments are presented in Tables 13, 14 and 15.

**Table 13.** Chemical composition after reverse flotation of calcined siderite ore

Product	Al <sub>2</sub> O <sub>3</sub>	CaO	Fe <sub>2</sub> O <sub>3</sub>	K <sub>2</sub> O	Na <sub>2</sub> O	P <sub>2</sub> O <sub>5</sub>	SO <sub>3</sub>	SiO <sub>2</sub>	MgO	MnO	TiO <sub>2</sub>	BaO	LOI
Feed	1.17	3.82	46.48	0.33	0.34	0.01	6.63	19.79	6.3	9.43	0.05	2.35	2.68
Float fraction	1.1	1.45	28.35	0.25	0.13	0.01	3.2	49.2	2.7	5.6	0.05	1.32	2.52
Pulp fraction	1.19	4.89	54.40	0.36	0.43	0.01	8.16	5.55	7.92	11.11	0.05	2.80	2.45

**Table 14.** Recovery of the iron after flotation

Product	Fe, %	Yield, %	Recovery, %
Feed	32.5	100.00	100.00
Float fraction	19.8	32.50	19.8
Iron product	38.0	67.50	80.2

**Table 15.** Recovery of SiO<sub>2</sub> after flotation

Product	SiO <sub>2</sub> , %	Yield, %	Recovery, %
Feed	19.79	100.00	100.00
Float fraction	49.2	32.50	80.8
Iron product	5.55	67.50	19.2

Results achieved after reverse flotation have been ~80% recovery of the iron in the *iron product* and ~81% recovery of SiO<sub>2</sub> in *float fraction*. Recovery of iron is relatively low compared to the flotation of raw ore. This effect is because of newly formed highly magnetic iron minerals infatuated in froth product together with silica minerals.

#### 4. Conclusion

Siderite ores from Kremikovci deposit are very difficult for beneficiation because of their mineral composition and liberation size. Provided magnetic separation experiments of raw siderite ore gave recovery of 81.1% with Fe content in concentrate 45.5%. Recovery of iron with

wet high intensity magnetic separation is high and also high is reduction of gangue minerals in the concentrate because except light minerals like quartz, dolomite, ankerite reduce also barite.

Electrostatic method for separation, according different conductivity of siderite from barite and quartz minerals gives almost the same Fe content in three products (conductor, middlings and non-conductor). This is due to fine particles of the liberated already siderite raw ore after grinding.

Gravity separation experiments in test 2 with 5 minutes grinding time and production of size fraction "30-100" μm - 55.25% recovery of iron in concentrate (heavy product) without calcination - 87.84%, instead of 84.46% received, after

calcination is a prerequisite for good application in siderite ore beneficiation. This high recovery of iron received has been achieved with relatively simple and low cost gravity separation. From provided experiments could be seen that such treatment of siderite ores achieved relatively low losses of iron in the tailings in one environmental friendly technology.

Recovery of iron of ~97% was produced after final stage of reverse flotation in experiments with raw siderite ore. Flotation process shows better selectivity than gravity separation and wet high intensity magnetic separation but final concentrate also have other contaminants like barite, dolomite and gangue minerals. After reverse flotation iron concentrate must be fed on another beneficiation operation to reduce more gangue minerals.

After provided experiments could be concluded that only one operation for beneficiation of siderite ore from Kremikovci deposit would not be enough for production of good enough for metallurgical use concentrate. Wet high intensity magnetic separation show in general acceptable recovery of iron and higher removal of gangue minerals from siderite ore as a single process for beneficiation than gravity, electrostatic separation and flotation. Further tests for combination of physical methods followed by physical-chemical treatment of siderite ore will be provided for finding optimal technology for enrichment.

## 5. References

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