-RESEARCH PAPER-

International Journal of Mining and Geo-Engineering

IJMGE

IJMGE 57-3 (2023) 315-321

DOI: 10.22059/IJMGE.2023.354748.595033

The effect of high voltage electric pulse on the coarse particle flotation of sulfur-bearing iron ore samples

Vahid Soltan Mohammadi [a,*], Mohammad Noaparast [a], Soheila Aslani [a]

[a] *School of Mining Engineering, College of Engineering, University of Tehran, Tehran, Iran.*

Article History:

Received: 06 February 2023.
Revised: 20 March 2023.
Accepted: 08 June 2023.

ABSTRACT

In this research, the effect of the high-voltage electric pulse (HVEP) crushing on the flotation of high-sulfur iron ore concentrate in the coarse particle fraction was studied compared to mechanical (conventional) crushing. A jaw crusher, a cone crusher, and a high-voltage electric pulse crushing device with a voltage level of 50 kV were used to investigate the effect of mechanical and electrical crushing. The results showed that a coarser particle product was produced with less slime in primary crushing with electric pulses compared to primary mechanical crushing. It was due to the crushing mechanism, which is based on separating minerals with a different dielectric constant from their connection boundaries and also encompasses a selective separation process. The effect of the mentioned method on coarser fractions led to the creation of cracks/microcracks in particle structures that made grinding easier and faster. In investigating the effect of particle size on pyrite flotation and desulfurization at -300 µm (d_{80}=300µm), the sulfur grade of flotation iron concentrate samples using primary crushing was 0.86% and 0.36%, respectively, and at -150 µm (d_{80}=150µm) fraction, the sulfur grade was found to be 0.33% and 0.19% respectively for mechanical and electrical methods. Also, the sulfur removal (recovery) of the sample with primary electrical crushing was 73.7% at a -300 µm fraction, almost equal to 73.2% at the size range of -150 µm with applying the mechanical method. These results indicated the flotation possibility of coarser particles using electrical crushing and desulfurization similarity to the samples with primary mechanical crushing in finer fractions**.**

Keywords: *High voltage electrical pulses, Grindability, Coarse particle flotation, Desulfurization, Iron ore.*

1. Introduction

Iron is one of the most common elements in the earth's crust, which nowadays is considered for processing due to the grade decreasing of iron ores and the increase of associated impurities such as sulfur [1]. The steel industry needs high purity and low impurity content iron to produce high-quality steel yet to minimize operating and maintenance costs [2, 3]. High amounts of sulfur in the iron ore sample hurt the process and quality of the produced iron [4]. The liberation of iron minerals from tailings requires crushing and grinding. To increase the quality levels of iron ore, the mineralization characteristics such as grade, particle size, distribution of minerals in ore deposits, and gangue minerals are essential. Also, they have a significant effect on the final size of ore crushing. In addition, by exceeding the crushing stages, processing and handling fine particles of iron ore samples become an essential challenge. The reason is identified as the complexity of the process by creating several steps in flowsheet improvement or even using different processing methods [5]. The industry is constantly seeking advanced ways to process complex deposits and reprocessing tailings to meet the needs of minerals and metals in multiple sectors. Nowadays, factories face several serious challenges, including a significant increase in power consumption, multi-staged crushing, mass production of slimes, a gradual decrease in the mineral's degree of liberation, inefficiency of classification devices, and maintenance and disposal issues. These cases have terrible consequences in energy consumption and environmental pollution in downstream operational units such as flotation, leaching, and filtration [6]. Generally, flotation is used as the main optimization technique to separate and increase the quality of iron ore [7, 8].

Flotation is a surface-selective separation method that separates hydrophobic materials from hydrophilic ones. Different reagents can selectively change the hydrophobicity of mineral surfaces, allowing a wide range of separations to be achieved [9, 10]. So far, the flotation technique has been the most common physicochemical separation approach in the mining industry, which processes more than two billion tons of primary and secondary resources annually. However, in any industrial flotation process, many precious minerals are transferred to the tailing sections as very fine and coarse particles. Therefore, coarse particle flotation can allow mines to properly separate some of the tailings early in the flotation circuit, significantly reducing capital and operating costs [11, 12]. The flotation of coarse particles is desirable for preventing excessive grinding and slime production. This, in turn, benefits tailings processing in the downstream units. Also, it reduces the milling process's energy consumption and operating costs [13]. In addition, slimes in the flotation process cause problems and reduce the product's efficiency, recovery, and quality.

Generally, three key factors are leading the mining industry to process coarse particles that are: 1) the severe environmental consequences of wet tailing dams and acid mine drainage (AMD) [14], 2) the loss of precious coarse materials [15], and 3) very high energy consumption in the ordinary crushing and grinding stages (2 to 4% of global electricity consumption) with less than 2% in efficiency[16]. Over the years, much work has been done to improve the iron ore flotation process, along with the reagents and equipment used, but less attention has been paid to improving the crushing process. The high voltage electric pulse (HVEP) method for crushing ore samples has been investigated for many years.

* Corresponding author: *Tel:* +98 2141868218, *E-mail address:* v.soltanmohammadi@gmail.com (V. Soltan Mohammadi).

Despite this, HVEP has not yet been developed as a competitive size reduction method compared to conventional mechanical crushing. Albeit, in recent years, this method has found great interest because of its advantages for downstream operating units [17].

High voltage electric pulse is based on applying tensile force in crushing. The separation of minerals from their connection boundary can effectively consume energy, achieve the appropriate degree of liberation in higher fractions, and produce less slime during crushing [18, 19]. One of the suggested HVEP applications is in the field of pre-processing operations. In this technology, electrical pulses with relatively low specific energy levels are discharged to segregate the mineral particles from the waste, followed by sieve sizing to classify the feed ore into high and low-grade products [20, 21]. Another advantage of HVEP is the cracks/micro-cracks created by blasting the ore electrical fracture channel at low energy levels, ultimately leading to energy savings in downstream crushing processes [22].

Wang et al. studied the difference in the liberation size of minerals resulting from mechanical and high-voltage electrical pulse crushing. The results showed that electric crushing improves the crushing process at the same energy levels by producing less slime and coarser particle products and promoting the degree of liberation of the processed minerals. In the case of degree of liberation, according to electric crushing, the liberated minerals were in the range of +53 µm. In contrast, in conventional crushing, the liberated minerals were obtained only at -53 µm fractions [23]. Andres et al. also studied the effects of HVEP crushing on five oxide and sulfide minerals. The results confirmed that the degree of liberation and slime production in ores containing hematite, platinum group metals, copper sulfides, and pentlandite was improved. Moreover, this improvement led to more mono-mineral particles in coarser size classifications [24].

Razavian et al. investigated the effect of the high voltage electric pulses crusher (HVEPC) on the phosphate ore compared to conventional crushers. Results showed that applying the high voltage pulses at a specific energy of 3–5 kWh/t could significantly increase and extend the cracks and microcracks inside the rocks and consequently lead to a decline in the Bond crushability and Abrasion indices of the crushed samples by 10.6% and 28.1%, respectively [25, 26]. Also, Finite Element results based on numerical simulation showed that the induced electrical field significantly depends on the electrical properties of minerals, the feed particle size, and the location of conductive minerals in ores [27, 28].

According to the literature, several studies have been conducted on electric pulse crushing. With that in mind, the effect of electric pulse crushing on coarse particle flotation of sulfur-bearing iron samples targeting desulfurization is still unstudied. In this research work, the effect of electric pulse crushing on mineral liberation and slime production is compared to mechanical crushing. Then, the affectability tests of coarse-size flotation for desulfurization were done for sulfur-bearing iron samples. The novelty of this research is the possibility of the coarse particle flotation to reduce the sulfur grade and content of iron ore by applying a high voltage electric pulse same results as the finer particle produced in the conventional crushing method.

According to the literature, several studies have been conducted on electric pulse crushing. With that in mind, the effect of electric pulse crushing on coarse particle flotation of sulfur-bearing iron samples targeting desulfurization is still unstudied. In this research work, the effect of electric pulse crushing on mineral liberation and slime production is compared to mechanical crushing. Then, the affectability tests of coarse-size flotation for desulfurization were done for sulfur-bearing iron samples. The novelty of this research is the possibility of the coarse particle flotation to reduce the sulfur grade and content of iron ore by applying a high voltage electric pulse same results as the finer particle produced in the conventional crushing method.

2. Experimental

2.1. Materials

This research provided high-sulfur iron ore samples from Gol Gohar mining and industrial company located in Sirjan, Iran. For experimental purposes, about 250 kg of high sulfur iron ore samples were selected with an initial size of -2 cm and then homogenized. According to sieve analysis, d_{80} of the initial sample was 11.26 mm. The XRD (Figure 1) and microscopic studies indicate that the sample mainly consisted of magnetite and chlorite. Also, hematite, pyrite, quartz, epidote, and pyroxene are present in the sample as secondary minerals. Microscopic studies showed that metallic minerals form about 70% of the sample, and the other 30% are gangue minerals (quartz, chlorite, etc.). Magnetite is the dominant metallic mineral which owns almost 90% of metallic minerals, and the rest is occupied with other metallic minerals. Hematite is considered in the second place of metallic mineral in the sample with an approximate abundance of 4-6%. Hematite is formed due to the martitization of magnetite samples and is observed as a replacement for magnetite. Pyrite, pyrrhotite, and goethite were also observed in the sample (2 to 4%). Polished and thin-polished sections and ZEISS Axioplan, two polarized light microscopes with reflected and transmitted light, were employed for mineralogical studies. Figure 2 shows the microscopic images of the initial sample at -300+150 µm fraction. As can be seen, there is the involvement of pyrite with magnetite and tailings, as well as the involvement of magnetite with tailings in this initial particle size range of the sample. The martitization phenomena or conversion of magnetite to hematite is also observable in this scheme.

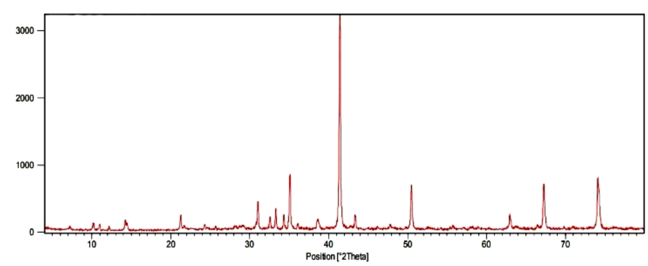

Figure 1. XRD pattern of the sample.

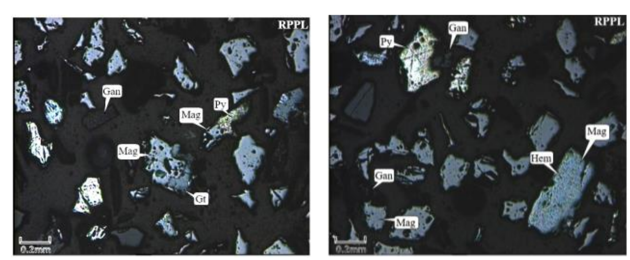

Figure 2. Microscopic images of the initial sample (-300+150 µm).

2.2. Methods

In this study, the first step was to separate the -3.36 mm fraction of the initial sample to investigate the effect of the type of crushing method on the degree of liberation of sulfur-bearing minerals (mainly pyrite) presented in the iron ore and desulfurization process, using flotation approach. Then, the prepared samples were divided into two parts for mechanical (conventional) and electrical crushing. In the mechanical method, a jaw crusher and a cone crusher were applied while in the electrical method, a high voltage electric pulse (HVEP) device was employed at the voltage level of 50 kV. Both samples were crushed finer than 3.36 mm. The crushed samples, prepared by mechanical and electrical methods, were subjected to mineralogical studies and chemical analysis in different fractions. As mentioned before, thin-polished and polished sections were investigated by ZEISS Axioplan 2 polarizing light microscope with reflected and transmitted light to study the degree of liberation in different fractions of the samples. The microscopic particle counting method has been used to determine the degree of liberation of minerals. In this method, liberated and involved grains were counted, and the degree of liberation was calculated from the following formula:

$$df = \frac{n_1}{n_1 + n_2} \times 100 \quad (1)$$

df: the degree of liberation of mineral
n_1: number of liberated minerals
n_2: number of involved minerals

The closed relationship between magnetite and hematite caused them to be considered as a whole in calculating the degree of liberation. It was the same for the sulfide minerals (pyrite and pyrrhotite).

After determining the degree of liberation of minerals, to mill down the crushed samples finer than 300, 210, 150, 106, and 75 µm, a rod mill was applied. A magnetic separation step was considered for preparing the samples for flotation tests. A roll low-intensity magnetic separator was selected, and variable parameters were set to 1000 gauss for the magnetic field, 45 rpm for roll speed, 25% for pulp density, and four lit/min for pulp inflow rate.

2.3. HVEP Pretreatment Equipment

A high-voltage electric pulse crusher (HVEP) was used in the Iran Mineral Processing Research Center (IMPRC) to conduct the electrical crushing tests. The schematic diagram of this equipment is shown in Figure 3. This device consists of two main parts: 1) the electric pulse generation circuit and 2) the main crushing chamber. The main crushing chamber has a conductive electrode rod made of copper, which transmits the shock wave generated from the electric circuit to the stone (Figure 4).

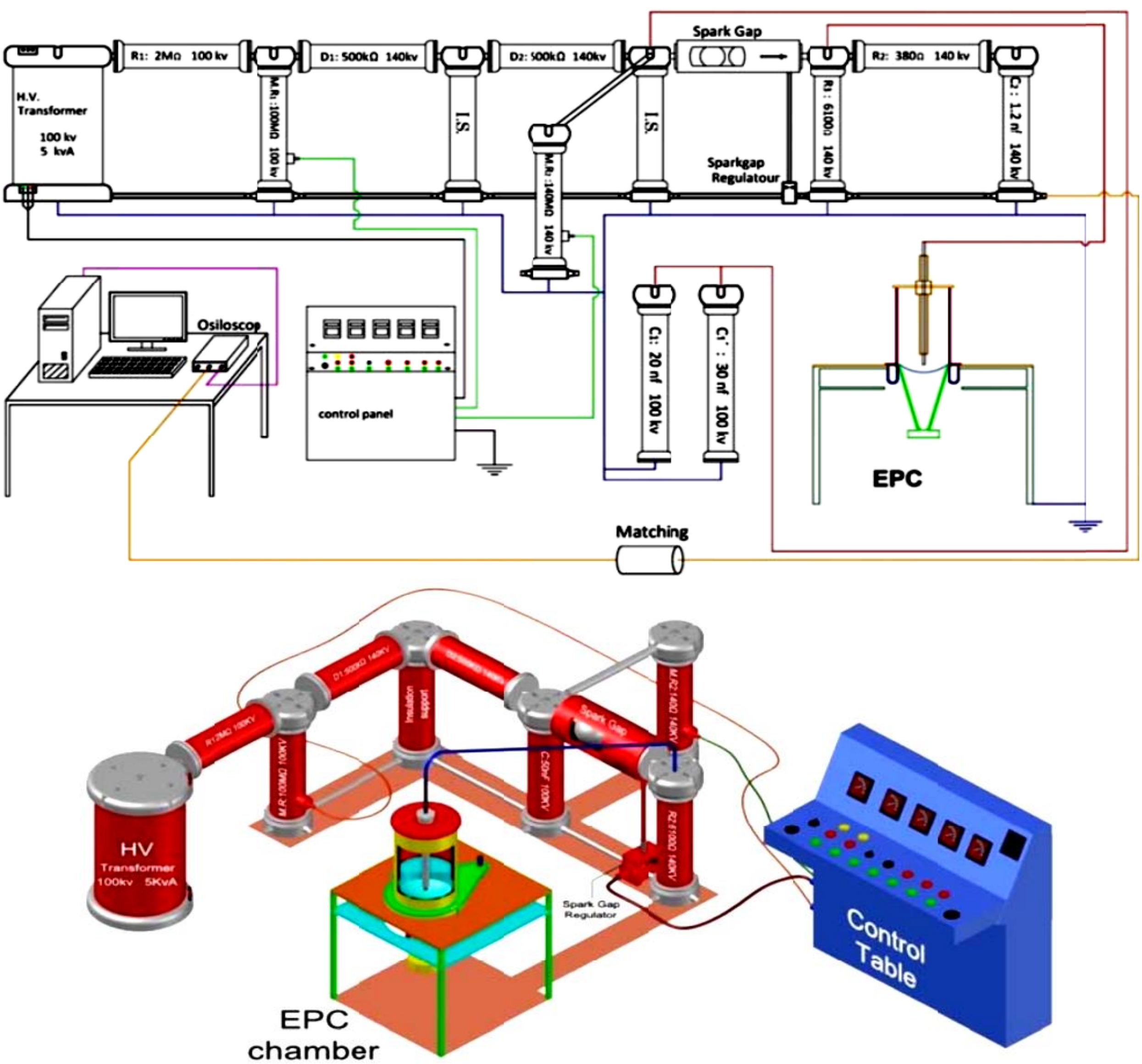

Figure 3. A schematic view of the employed HVEP [28].

2.4. Flotation test

In this research, a Denver mechanical flotation cell was utilized for the desulfurization of pyrite through reverse-flotation experiments, and the cell was fed with the concentrate of the magnet separator. After optimizing the type and the amount of chemical reagent by performing the flotation tests with primary mechanical crushing, the upcoming flotation tests were carried out under optimal conditions. According to Figure 5, a series of experiments were performed to reduce the existing sulfur in the iron ore concentrate. Adding 150 g/ton of hydrogen sodium sulfide as an activator, 100 g/ton of potassium amyl xanthate as a collector, and 100 g/ton of methyl isobutyl carbonyl as frother were selected. The pulp density for the experiments was adjusted to 25%, and the pH of the pulp was kept natural (about 8). Five different fractions with d_{80} equal to 75, 106, 150, 210, and 300 μm of the samples were selected for primary crushing. Both mechanical and electrical methods were employed, and the results were accordingly compared and discussed.

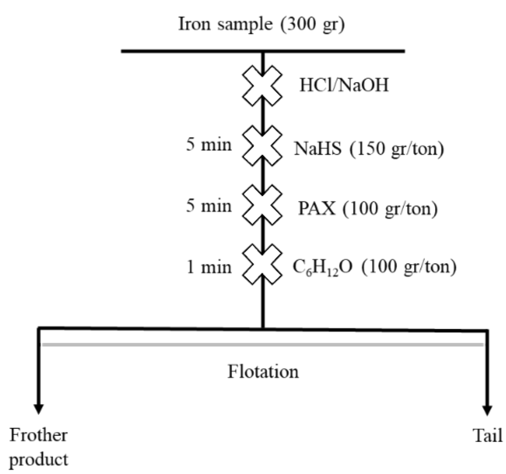

Figure 5. Flotation flowsheet of the mineral sample.

3. Results and discussion

3.1. Comparison of HVEP and Mechanical crushing

3.1.1. Coarse and fine (slime) particle production

According to the sieve analysis of the crushed samples by mechanical and electrical methods in Figure 6, only 1.7% of the electrically crushed samples were finer than 38 μm. In comparison, 8.5% of the mechanically crushed samples were classified as finer than 38 μm. These numbers indicate less slime production during electrical crushing, which is related to tensile forces and the separation of minerals from their connection boundaries compared to mechanical crushing. In addition, according to Figure 7, at the size range of +1000 μm, the percentage of remaining particles on the sieve in the electrically crushed sample is higher than in the mechanically crushed one. In electrical crushing, about 45% of the cumulative particles were coarser than the +1000 μm fraction, which decreased to 25% for the mechanical method. Also, at -1000 μm, the weight percentage of the produced particles by mechanical crushing was higher than the electrical crushing method. In general, coarser particles with low slimes were obtained in electrical crushing compared to mechanical crushing.

For this reason, d_{80} of the electrically and mechanically crushed products were measured to be 2069 and 1346 μm, respectively. In electric pulse crushing, the production of coarse-sized particles with less slime is caused by the difference in the dielectric constant of distinct minerals and tensile forces, which lead to the separation of minerals from their contact boundaries. This results in a selective separation process with a higher degree of liberation. The main mechanisms in mechanical crushing include impact (compressive force) and abrasion (shearing force), which leads to non-selective crushing, a lower degree of liberation of the minerals, and more slime production.

3.1.2. Degree of liberation of sulfide and iron minerals

The degree of liberation of sulfide and iron-bearing minerals resulting from mechanical and electrical crushing was gathered in Table 1. It can be understood from Table 1 that in all size fractions, the degree of liberation of sulfide and iron-bearing minerals in the electrical crushing method was higher than in mechanical crushing, which indicates a positive sign of the effect. As mentioned before, the electrical crushing mechanism is based on the possibility of separating minerals from their connection boundaries. Thus, it can be inferred that the electrical crushing mechanism causes a positive effect on the degree of liberation of the minerals. The degree of liberation of magnetite-hematite minerals in the range of -300+150 μm was calculated to be 75% for the mechanically crushed sample and 79% for the electrically crushed one. In the same size fraction, the degree of liberation of sulfur-bearing minerals (mainly pyrite) was calculated to be 52% for a mechanically crushed sample and 60% for an electrically crushed one.

3.1.3. The grinding time and the grinding rate

According to the grinding time graph in Figure 8, during the first three minutes of grinding, the d_{80} of the sample with primary mechanical crushing reached from 1346 to 455 μm (66% reduction in size), while the d_{80} of the sample with primary electrical crushing went from 2069 to 333 μm (84% reduction in size). Therefore, on average, the grinding rate at this time interval and size range is expressed as about 300 μm per minute for the sample with primary mechanical crushing and about 580 μm per minute for the sample with primary electrical crushing. Nevertheless, in the seventh minute of grinding, the d_{80} of the sample with primary mechanical crushing reached 455 to 222 μm (about a 52% reduction in size). In comparison, the d_{80} of the sample with primary electrical crushing reached 333 to 208 μm (about a 37% reduction in size). Therefore, at this time interval and size range, the average grinding rate for the sample with primary mechanical crushing was about 58 μm per minute and 31 μm per minute for the sample using primary electrical crushing. In addition, by increasing the grinding time along with particle size reduction, milled samples in both methods almost became the same size. However, with 31 minutes of grinding, both milled samples reached the size range of d_{80}=50 μm. The results proved that primary electrical crushing makes grinding operation much easier and faster. The reason can be found in the effect of this crushing on coarser fractions and the creation of cracks/microcracks. However, due to the abrasion mechanism in the primary mechanical crushing, the grinding rate of finer particles was higher in finer fractions.

3.1.4. Iron and sulfur grades

According to the investigation on the effect of the crushing method on iron and sulfur grade in Figure 9, the trend of iron grade is almost similar in both mechanical and electrical crushing ways for all size fractions. The maximum iron grade was obtained at -500+150 μm and reached about 55%.

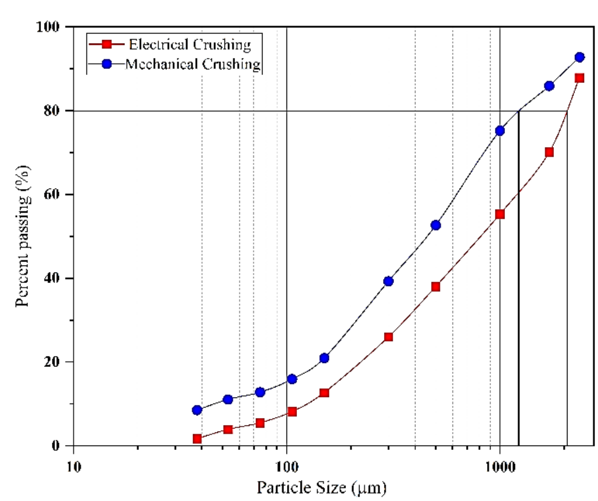

Figure 7. The percentage of remaining particles on the sieve and the -38 μm fraction related to the crushed samples by mechanical and electrical methods.

Table 1. Comparison of degrees of liberation resulted from mechanical and electrical crushing.

Pyrite-Pyrrhotite (%)		Magnetite-hematite (%)		Particle Size (µm)
Mechanical Crushing	Electrical Crushing	Mechanical Crushing	Electrical Crushing	
52	60	75	79	-300+150
73	76	85	89	-150+106
82	88	-	-	-106+75

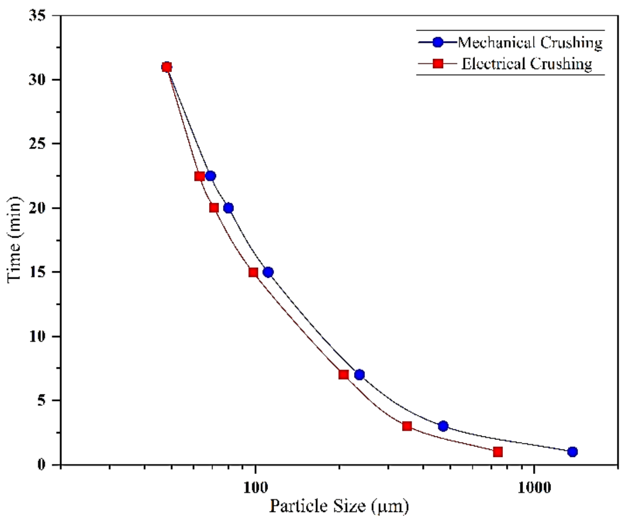

Figure 8. Grinding time graph related to mechanical and electrical crushing.

The iron grade decreased using both crushing methods on both sides of this particle size range. So, at fractions finer than 150 µm, the iron grade with primary electrical crushing decreased to about 40%, while in the case of primary mechanical crushing, it decreased to 15%. At the size range of +500 µm, the iron grade was calculated to be 47% for the electrically crushed sample and 42% while using the mechanical crushing method. Figure 10 represents the dissimilarity of sulfur grades at -300 µm fractions according to the applied crushing methods. The sulfur grade maintained its uptrend path by employing the electrical crushing at the mentioned fractions and reached its maximum amount (3.3%) at -53+38 µm size fraction. The sulfur grade formed a downtrend pattern about the primary mechanical crushing and touched 0.7% as its minimum amount at the size range of -38 µm. At the +300 µm, the sulfur grade increased with almost an increasing pattern for both crushing methods. When the considered size fractions in primary electrical crushing varied from -500+300 µm to +1000 µm, the sulfur grade increased from 1.76% to 2.2%. The maximum sulfur grade in this crushing method (primary electrical crushing) was achieved at -300 µm fractions. This subject confirms a fast and selective crushing for sulfurous minerals while employing high voltage electric pulse primary crushing instead of primary mechanical crushing. Also, these minerals will be classified in finer size fractions.

3.2. Effect of HVP on Sulfur flotation

To investigate the effect of particle size on desulfurization and pyrite flotation, separate concentrations of low-intensity magnetic separators with different primary crushing methods and d_{80}=300, 210, 150, 106, and 75 µm were selected for the reverse flotation tests. In each mentioned particle size, two types of samples were prepared, one initially for the electrical pulse crushing method and the other for the mechanical one, and flotation tests were carried out under the same optimum conditions. According to Figure 11, at finer fractions (i.e., d_{80}=106 µm and d_{80}=75 µm), the grade of flotation products in both mechanical and electrical crushing methods was almost similar. At coarser size ranges, the effect of the crushing process on desulfurization was recognized in the grade difference of flotation products. So, at d_{80} = 300 µm, the sulfur grade of iron concentrate in the flotation of samples with initial mechanical and electrical crushing was measured 0.86% and 0.36%, respectively. In addition, at d_{80}=150 µm, the sulfur grade was reported to be 0.33% for mechanically crushed samples and 19% for electrically crushed ones. According to the results, it can be concluded that applying the electrical crushing method makes the flotation of coarser sulfurous iron ore particles possible. In addition, the results showed the similarity of the desulfurization with the finer particles of primary mechanical crushing. Figure 12 indicates that in the same size classes, the weight recovery of the floated part (containing sulfur-bearing minerals) of the electric crushing samples was higher than the mechanically crushed ones. Moreover, the maximum weight recovery of the floated part in both primary mechanical crushing and electric pulse methods was 4% and 5.7%, respectively, at d_{80}=150 µm fraction.

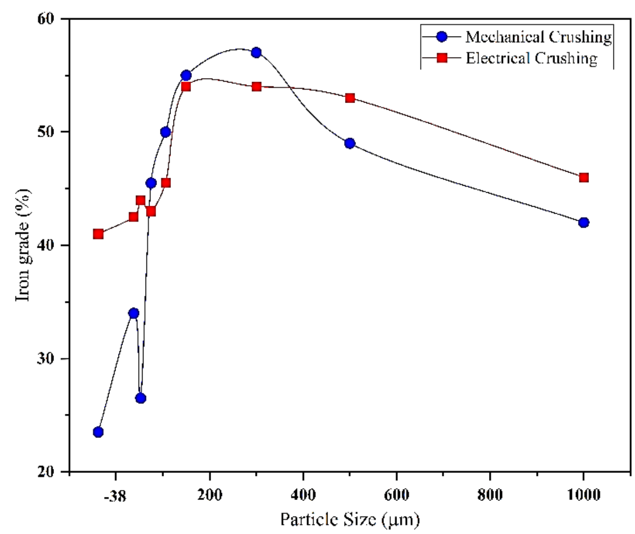

Figure 9. The effect of the crushing method on the trend of iron grade in different size fractions.

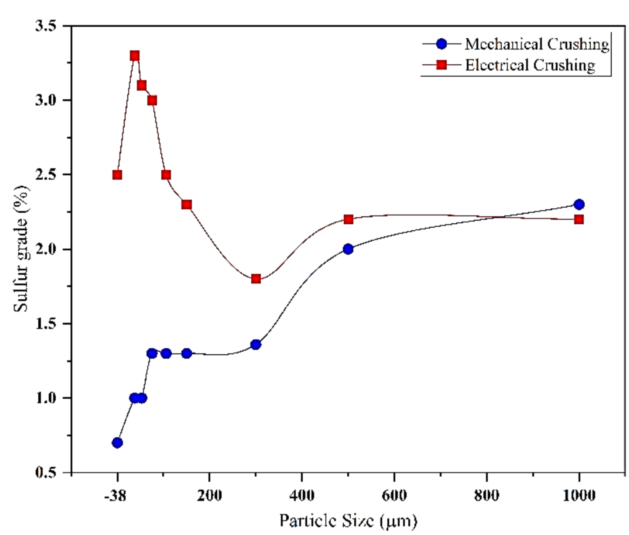

Figure 10. The effect of the crushing method on the trend of sulfur grade in different size fractions.

At the size range of +210 μm, the graph of mechanical crushing changed its character to the downside trend compared to the electrical crushing chart. Therefore, in the sample with primary mechanical crushing, the minimum weight recovery (3.1%) was achieved at the size range of d_{80}=300 μm. Meanwhile, the weight recovery of the floated part at d_{80}=300 μm fraction was equal to 4.9% for the samples with primary electrical crushing, which is higher than the maximum weight recovery (4%) of the sample with mechanical crushing at d_{80}=150 μm fraction. It would be resulted from Figure 13 that in finer fractions (d_{80}=106 μm and d_{80}=75 μm), the amount of recovered sulfur in both electrical and mechanical grinding methods is almost the same. Sulfur removal from the samples at +150 μm was different for both crushing techniques.

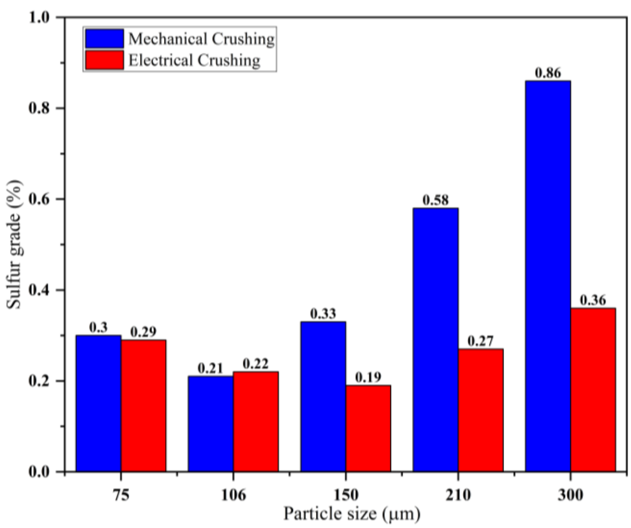

Figure 11. Effect of the particle size on the sulfur grade of the flotation product by employing electrically and mechanically crushed samples.

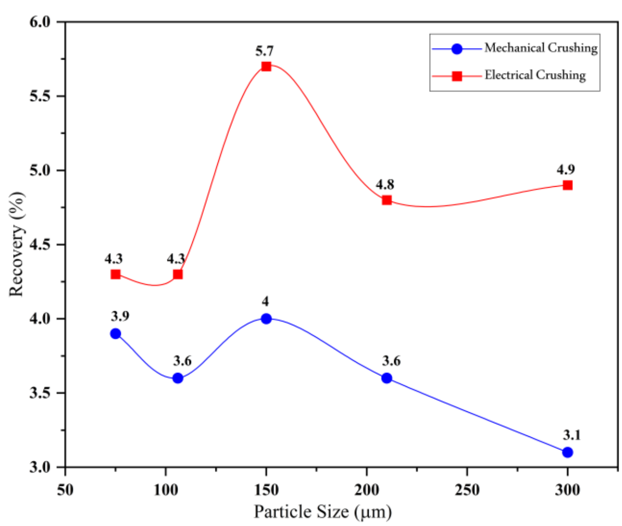

Figure 12. Effect of particle size on weight recovery of flotation product by employing electrically and mechanically crushed samples.

The maximum sulfur removal was 83.8% for the electrically crushed samples at d_{80}=150 μm, and the minimum sulfur removal was 44.4% obtained by mechanical method at d_{80}=300 μm. Meanwhile, the sulfur removal at d_{80}=300 μm of the electrically crushed sample was 73.7%, almost equal to the sulfur removal amount (73.2%) of the mechanically crushed sample with d_{80}=150 μm. The sample with primary electrical crushing at d_{80}=300 μm fraction acted similarly to the mechanically crushed method at d_{80}=150 μm. Moreover, its sulfur grade and recovery were similar to the products at d_{80}=75 μm, which were crushed by

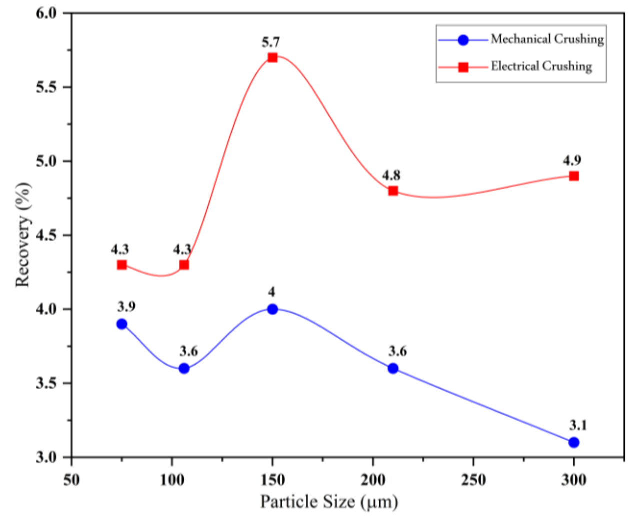

Figure 13. Effect of particle size on recovery of the flotation product by employing electrically and mechanically crushed samples.

mechanical or electrical processes. Based on this, it can be concluded that by using high-voltage electric pulse crushing, the flotation possibility of coarse-sized particles and sulfur content removal is similar to samples with primary mechanical and sometimes electrical crushing at finer fractions. In addition, a coarse particle product with a higher degree of liberation and less slime was obtained.

4. Conclusion

This research work studied the effect of the primary crushing (mechanical and electric pulse) on particle sizes to investigate the flotation possibility of coarse particle high-sulfur iron ore samples using electric pulse crushing. The following results were made according to the different crushing and flotation tests.

Electric pulse crushing produced a coarse particle product with less slime compared to the mechanical (conventional) method. Moreover, the degree of liberation of iron and sulfur-bearing minerals in electrical crushing methods was higher than mechanical crushing in all size fractions. These were due to the difference in the dielectric constant of the minerals and the effect of tensile force in the size reduction using electric pulse crushing, which led to the selective separation of minerals from the contact boundaries. In the sample primarily crushed by electric pulses, creating cracks/microcracks in the structure of coarse-sized particles made them easier to mill in the initial grinding stages. Besides, the grinding process was operated faster and much easier.

In mechanical crushing, the sulfur grade increased as particle size increased. In electric pulse crushing, the sulfur grade decreased until the range of -500+300 μm; after that fraction, it grew to some extent. This subject confirmed a fast and selective crushing for sulfurous minerals while employing high voltage electric pulse primary crushing instead of primary mechanical crushing. These minerals were classified into finer-size fractions.

The flotation of pyrite proved that both crushed samples, with different methods, had similar results in desulfurization at the range of d_{80}=106 and 75 μm. However, the sulfur grade and its removal were reported at 0.33% and 73.2% in mechanical crushing and 0.19% and 83.8% in electrical crushing, respectively, at d_{80}=150 μm. At the d_{80}=300 μm, the sulfur grade and removal obtained 0.86% and 44.4% in mechanical crushing and 0.36% and 73.7% in the electrical method, respectively. So, it means the primary crushing method (mechanical and electrical) had a high effect on the flotation of samples from d_{80}=150 μm to coarser fractions in terms of grade difference and sulfur removal from the iron ore concentrate. In addition, the sample with primary electric crushing at d_{80}=300 μm acted similarly to the sample with primary mechanical crushing at d_{80}=150 μm fraction.

REFERENCES

[1] Yu, K.-p., Yu, Y.-f., and Xu, X.-y. (2013). Separation behavior and mechanism of hematite and collophane in the presence of collector RFP-138. Transactions of Nonferrous Metals Society of China, 23(2): p. 501-507. doi: https://doi.org/10.1016/S1003-6326(13)62491-7

[2] Arol, A.I., & Aydogan, A. (2004). Recovery enhancement of magnetite fines in magnetic separation. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 232(2-3): p. 151-154. doi: https://doi.org/10.1016/j.colsurfa.2003.06.003

3[] F Filippov, L., V. Severov, & Filippova, I. (2014). An overview of the beneficiation of iron ores via reverse cationic flotation. International journal of mineral processing, 127: p. 62-69. doi: https://doi.org/10.1016/j.minpro.2014.01.002

[4] Yu, J., Ge, Y., & Cai, X. (2016). The desulfurization of magnetite ore by flotation with a mixture of xanthate and dixanthogen. Minerals, 6(3): p. 70. doi: https://doi.org/10.3390/min6030070

[5] Mathur, S., Singh, P., & Moudgil, B. (2000). Advances in selective flocculation technology for solid-solid separations. International Journal of Mineral Processing, 58(1-4): p. 201-222. doi: https://doi.org/10.1016/S0301-7516(99)00072-1

[6] Mudd, G.M. (2007). The sustainability of mining in Australia: key production trends and their environmental implications. Department of Civil Engineering, Monash University and Mineral Policy Institute, Melbourne.

[7] Araujo, A., Viana, P., & Peres, A. (2005), Reagents in iron ores flotation. Minerals Engineering, 18(2): p. 219-224. doi: https://doi.org/10.1016/j.mineng.2004.08.023

[8] Nakhaei, F. & Irannajad, M. (2018). Reagents types in flotation of iron oxide minerals: A review. Mineral Processing and Extractive Metallurgy Review, 39(2): p. 89-124. doi: https://doi.org/10.1080/08827508.2017.1391245

[9] Carlson, J. & Kawatra, S. (2013). Factors affecting zeta potential of iron oxides. Mineral Processing and Extractive Metallurgy Review, 34(5): p. 269-303. doi: https://doi.org/10.1080/08827508.2011.604697

[10] Rao, S.R. (2013). Surface chemistry of froth flotation: Volume 1: Fundamentals. Springer Science & Business Media.

[11] Hassanzadeh, A., et al. (2022). Technological assessments on recent developments in fine and coarse particle flotation systems. Minerals Engineering, 180: p. 107509. doi: https://doi.org/10.1016/j.mineng.2022.107509

[12] Lakshmanan, V.I. & Gorain, B. (2019). Innovations and Breakthroughs in the Gold and Silver Industries: Concepts, Applications and Future Trends. Springer.

[13] Awatey, B., et al. (2013). Optimization of operating parameters for coarse sphalerite flotation in the HydroFloat fluidised-bed separator. Minerals Engineering, 50: p. 99-105. doi: https://doi.org/10.1016/j.mineng.2013.06.015

[14] Nwaila, G.T., et al. (2021). Valorisation of mine waste-Part I: Characteristics of, and sampling methodology for, consolidated mineralised tailings by using Witwatersrand gold mines (South Africa) as an example. Journal of Environmental Management, 295: p. 113013. doi: https://doi.org/10.1016/j.jenvman.2021.113013

[15] Safari, M., Harris, M., & Deglon, D. (2018). The effect of energy input on the flotation of a platinum ore in a pilot-scale oscillating grid flotation cell. Minerals Engineering, 2017. 110: p. 69-74. doi: https://doi.org/10.1016/j.mineng.2017.04.012

[16] Hassanzadeh, A. (2018). A survey on troubleshooting of closed-circuit grinding system. Canadian Metallurgical Quarterly, 57(3): p. 328-340. doi: https://doi.org/10.1080/00084433.2018.1464618

[17] Zuo, W., et al. (2020). Effect of high voltage pulse treatment on the surface chemistry and floatability of chalcopyrite and pyrite. Minerals Engineering, 147: p. 106170. doi: https://doi.org/10.1016/j.mineng.2019.106170

[18] Andres, U. (2010). Development and prospects of mineral liberation by electrical pulses. International Journal of Mineral Processing, 97(1-4): p. 31-38. doi: https://doi.org/10.1016/j.minpro.2010.07.004

[19] Yan, G., et al. (2020). Investigating the influence of mineral characteristics on induced effect of high-voltage pulse discharge by synthetic minerals. Minerals Engineering, 153: p. 106380. doi: https://doi.org/10.1016/j.mineng.2020.106380

[20] Shi, F., et al. (2014). A potential application of high voltage pulse technology in a gold-copper ore grinding circuit. IMPC 2014-27th International Mineral Processing Congress, Gecamin Digital Publications.

[21] Shi, F., Zuo, W., & Manlapig, E. (2015). Pre-concentration of copper ores by high voltage pulses. Part 2: Opportunities and challenges. Minerals Engineering, 79: p. 315-323. doi: https://doi.org/10.1016/j.mineng.2015.01.014

[22] Wang, E., Shi, F., & Manlapig, E. (2011). Pre-weakening of mineral ores by high voltage pulses. Minerals Engineering, 24(5): p. 455-462. doi: https://doi.org/10.1016/j.mineng.2010.12.011

[23] Wang, E., Shi, F., & Manlapig, E. (2012). Mineral liberation by high voltage pulses and conventional comminution with same specific energy levels. Minerals Engineering,. 27: p. 28-36. doi: https://doi.org/10.1016/j.mineng.2011.12.005

[24] Andres, U., Timoshkin, I., & Soloviev, M. (2001). Energy consumption and liberation of minerals in explosive electrical breakdown of ores. Mineral Processing and Extractive Metallurgy, 110(3): p. 149-157. doi: https://doi.org/10.1179/mpm.2001.110.3.149

[25] Razavian, S.M. (2014). Effect of High Voltage Electric Pulses on Phosphate Ore Comminution. PhD Thesis, Amirkabir University of Technology.

[26] Razavian, S.M., Rezai, B., Irannajad, M. (2014) Investigation on Pre-weakening and Crushing of Phosphate Ore Using High Voltage Electric Pulses. Advanced Powder Technology, Vol. 25, pp. 1672-1678. doi: https://doi.org/10.1016/j.apt.2014.06.010

[27] Razavian, S.M., Rezai, B., Irannajad, M. (2015). Finite Element Method Based Simulation of Electrical Breakage of Iron-Phosphate Ore. PPMP Journal, Vol 51 (1), pp. 137-150. doi: http://dx.doi.org/10.5277/ppmp150113

[28] Razavian, S.M., Rezai, B., Irannajad, M., Ravanji, M.H. (2015). Numerical Simulation of High Voltage Electric Pulse Comminution of Phosphate Ore, IJMST, Vol. 25 (3), pp. 473-478. doi: https://doi.org/10.1016/j.ijmst.2015.03.023