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Effect of crushing type on the efficiency of flowing film separation

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Abstract: In recent years, the influence of different crushing systems (compression, impact, attrition) has been receiving more attention due to their significant role on particle liberation and shape of particles. The objective of this study was to investigate the effects of different crushing systems on both liberation degree and shape factors of chromite particles along with their enrichment conditions by shaking table. The tests were conducted on -1+0.5, -0.5+0.212 and -0.212 mm size fractions using the Wilfley type shaking table. The results of these tests showed that concentrates with higher metal contents were obtained by impact crushing of chromite in proportion to higher liberation degree and roundness of particles. Therefore, it was found that selective breakage can well be obtained by impact crushing in all fractions. The results of this study demonstrated the importance of crushing type on the liberation and enrichment processes.

Keywords: *particle shape characteristics, liberation degree, chromite, shaking table*

1. Introduction

Comminution mainly addresses the size reduction of rocks required to liberate the valuable minerals associated with gangue and enable their recovery with suitable separation processes (Weerasekara et al., 2013; Little et al., 2016,). In order to control the quality of products and size reduction processes, different types of breakage mechanisms such as compression, impact or abrasion/attrition are applied via various crushers. For instance, in impact mechanism, the crusher hits one of the corner and accelerates, rotates the particles and disintegrates a part of it (Unland and Al-Khasawneh, 2009). On the other hand, in compressive breakage, different crushing zones will be formed and depending on the position of particle in the crushing chamber, the breakage occurs by single particle breakage or inter-particle breakage (Lee and Evertsson, 2013). Indeed, that situation also depends on the level of crushing chamber where particle bed occurs (Evertsson et al. (2000) as cited in Evertsson et al. (2013)). In other words, in compression breakage, particles fail when the uniaxial compressive strength was exceeded (Yahyaei et al., 2016). In abrasion/attrition mechanisms, shear effect is used for the breakage of particles and while moving parallel to contact surfaces of particles, finer ones are nipped by two larger particles which cause substantial damage to the main body of them (Yahyai et al., 2016). Consequently, particles are broken randomly or selectively through the boundaries between two minerals. Therefore, the optimization of crushing process for selectively breakage will not only avoid the overgrinding costs but also provide liberation before pre-concentration processes. The particle breakage along mineral boundaries and selective breakage were schematically shown in Fig. 1.

Besides the importance of breakage type, the quality of products after concentration process is closely related to the size distribution of minerals and physical properties of particles as shape (Hosten and Ozbay, 1998).

The objective of this study is to investigate and compare the effects of both impact and compressive type of crushing on physical characteristics of chromite particles and their effects on gravity concentration by shaking table.

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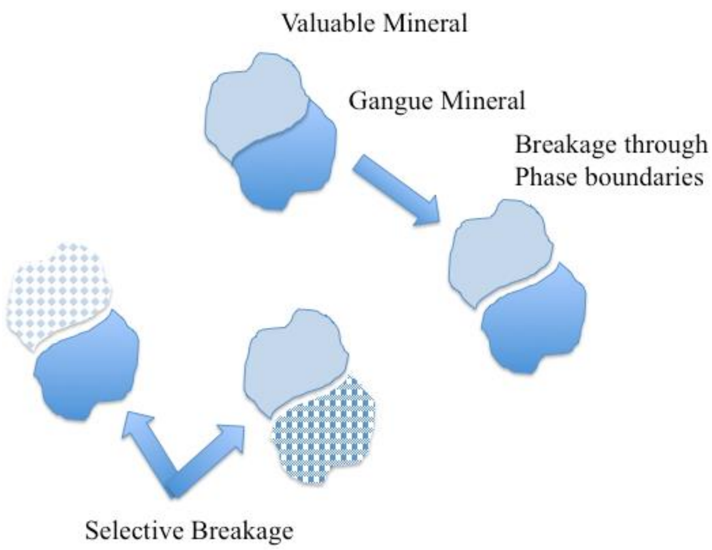

Fig. 1. Schematic representation of breakage patterns of mineral particles

2. Materials and methods

In this study, chromite sample collected from Kayseri-Pınarbasi district was used. The maximum particle size in run of mine ore sample was 5 cm and the Cr_2O_3 content of product was 17.8 %. According to the mineralogical analysis, main gangue minerals were found to be olivine and serpentine. For experimental studies, the sample was initially divided into two parts by cone and quartering method. Half of the sample was crushed below 1 mm by adapting a series of crushers including jaw, cone and roll crushers (hereafter compression breakage) and the other half was directly crushed by impact crusher (hereafter impact breakage). Crushed samples were then screened out into three size ranges as -1+0.5; -0.5+0.2 and -0.2 mm. The Cr_2O_3 analysis of run of mine ore and products were carried out by X-Ray Fluorescence (XRF) analysis. Following the crushing processes, those fractions were used in the enrichment tests with laboratory scale Wilfley shaking table and liberation degree analysis with particle counting method with binocular microscope. In addition, the products of shaking table tests were analyzed for their shape factors with Image Analysis technique in order to determine the relation between shape and enrichment rate along with the crushing type and liberation degree.

2.1 Crushing tests

As mentioned in the Introduction section, different mechanisms namely "compression, attrition or impact effect" occur during breakage of particles depending on the machinery used. As a result, the particles are broken randomly or along the boundaries between two minerals. In other words, upon higher selective breakage ratios, it is possible to avoid overgrinding or increase the ratio of liberation. Considering this knowledge, in this study, different types of crushers were used in order to compare different crusher types for preferential breakage and higher liberation degree of particles. For this aim, pilot scale jaw + cone + roll crusher combination was tested for compressive breakage while only impact crusher was used for impact breakage. In addition, it is worth to note that, particles were fed individually during all crushing works in experimental studies.

2.2 Morphological characterization

Particle shape plays a vital role in many areas including mineral processing, plastics and other particle based processes in terms of interaction with each other or in a separation medium. Image analysis is the most common method for the determination of these parameters while other methods like Fourier analysis can also be used for different scopes (Mahmoud, 2010). In this study, shape factors of crushed materials were determined using the images obtained with a binocular microscope and analyzed by Leica Q Win Image Analyze software (Leica Qwin User Manual, 1995) based on the particle projections from the micrographs of particles. Besides other shape factor parameters like aspect ratio, relative width, only roundness was used for evaluating the shape characteristics of products. Thus, "roundness" is the most common parameter for evaluating the effect of particle shape during particle based processes. The value of this parameter was automatically calculated for at least 100 particles by adapting the equation given below:

$$Roundness\ (Ro) = \frac{4\pi A}{P^2}. \tag{1}$$

In equation 1, where, P is the perimeter, A is the area of the particle determined by the software. In literature, this equation is also used for calculation of circularity parameter (Little et al., 2015). However, we adapted this equation from a recent article for the definition of roundness (Guven et al., 2016). Thus, characterization of particle morphology is not only important for particle characterization but also a definitive parameter for the evaluation of interactions during different processes like flotation, coagulation (Koh et al., 2009, Vizcarra et al., 2011, Verelli et al. 2014, Little et al., 2015, Guven et al., 2015, Hassas et al., 2016).

2.3 Analysis of liberation degree

The liberation degree of chromite particles in each fraction was analyzed under ore microscope for measuring the degree of liberation of chromite by particles counting method. In this method, the number of liberated and locked particles were noted and the percentage liberation degree at various size fractions were calculated with the equations given below:

$$Liberation\ Degree\ (\%) = \frac{NLVM}{NLGM} x\ 100 \tag{2}$$

$$Total\ Liberated\ Mineral = NLVM + (\ (VML)\ x\ 1{,}4) \tag{3}$$

$$Liberated\ mineral\ (wt.\%) = \frac{(NLVM+VML)x\ (\ d_{VM})}{(NLVM+VML)x\ (\ d_{VM})+(NLGM+GML)x(\ d_{GM})} x\ 100. \tag{4}$$

In these equations, *NLVM* and *NLGM* accounts for the numbers of liberated valuable and gangue minerals respectively. Likewise, *VML* and *GML* are the amount of valuable and gangue mineral in locked form respectively.

3. Results and discussion

In this study, afore-mentioned size fractions such as -1+0.5, -0.5+0.212 and -0.212 mm were analyzed for their liberation degree and the products of shaking tables were re-analyzed for their shape factor values. First, the size distributions of crushed materials with different series of crushers were found. The size distribution after both crushing type showed a similar trend, where only slight differences were obtained for the increment in fines in the case of impact crushing processes. As shown in Table 1, weight of finer size under 0.5 mm is slightly higher for the products of impact crushing to compression. In Table 1, the size distributions and the Cr_2O_3 contents of crushed materials were shown for both crushing types.

Thus, if the higher metal contents of finer fractions in impact crushing were considered, the higher the amount of fines can be explained in terms of more liberate particles. Therefore, in order to prove our hypothesis, we performed shaking table experiments under the same conditions such as the angle of the table, feed speed, amount of water etc. The concentration process flowsheet was given in Fig. 2.

Table 1. Size distribution and Cr_2O_3 % content of respective crushing types

Size Fraction, mm	Compression Crushing			Impact Crushing		
	Weight, %	Cr_2O_3, %	Distribution, %	Weight, %	Cr_2O_3, %	Distribution, %
-1+0.5	41.1	13.73	32.1	37.5	9.81	20.5
-0.5+0.212	19.3	21.02	23.0	19.5	22.50	24.5
-0.212	39.6	19.98	44.9	43.0	22.98	55.1
Total	100.0	17.91	100.0	100.0	17.95	100.0

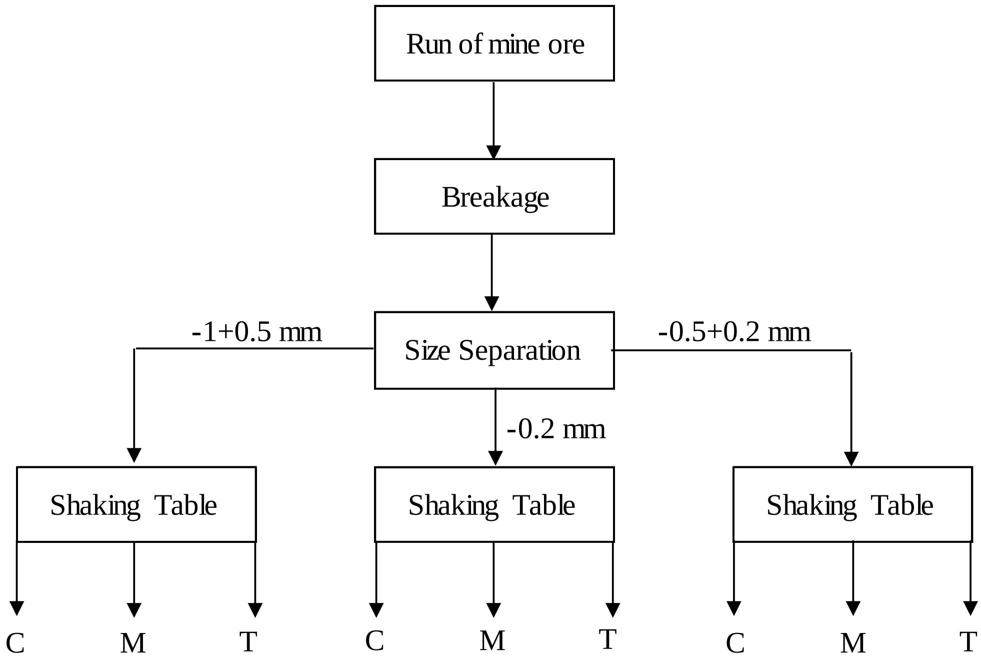

Fig. 2. The concentration process flowsheet with different types of crushed chromite samples

During these processes, only one stage enrichment was applied. All products were collected, dried, weighed and sent for Cr_2O_3 % content analysis. In Tables 2-4, the results of shaking table tests using compression and impact crushing were given. It was found that the metal content of concentrates was almost the same. However, when only middling product was taken into consideration, both the metal contents and recovery values were considerably higher in impact crushing except -1+0.5 mm size fraction.

If the results of all fractions are approximately combined (Table 5), the difference between crushing types becomes clearer and for concentrates with similar metal contents the recovery is over 25 % higher in impact crushing compared to compression crushing.

Table 2. The results of tests conducted with -1+0.5 mm size fraction of both compression and impact breakage

	Compression Crushing			Impact Crushing		
Products	wt. %	Cr_2O_3, %	ε, %	wt. %	Cr_2O_3, %	ε, %
Concentrate	14.2	43.75	45.2	15.4	43.65	68.4
Middlings	42.3	13.30	41.0	34.6	5.30	18.7
Tailings	43.5	4.36	13.8	50.0	2.53	12.9
Feed	100.0	13.74	100.0	100.0	9.82	100.0

Table 3. The results of tests conducted with -0.5+0.212 mm size fraction of both compression and impact breakage

	Compression Crushing			Impact Crushing		
Products	wt. %	Cr_2O_3, %	ε., %	wt. %	Cr_2O_3, %	ε, %
Concentrate	28.3	50.29	67.7	26.1	51.44	59.7
Middlings	27.1	21.67	27.9	28.0	28.22	35.1
Tailings	44.6	2.08	4.4	45.9	2.54	5.2
Feed	100.0	21.03	100.0	100.0	22.49	100.0

Table 4. The results of tests conducted with -0.212 mm size fraction of both compression and impact breakage

	Compression Crushing			Impact Crushing		
Products	wt. %	Cr_2O_3, %	ε, %	wt. %	Cr_2O_3, %	ε, %
Concentrate	19.1	51.68	49.4	13.5	53.30	31.3
Middlings	26.8	28.67	38.4	35.5	35.23	54.4
Tailings	40.2	3.25	6.5	28.0	3.05	3.7
Slimes	13.9	8.12	5.6	23.0	10.57	10.6
Feed	100.0	19.99	100.0	100.0	22.99	100.0

Table 5. Combined results of tests conducted with -0.212 mm size fraction of both compression and impact breakage

	Compression Crushing			Impact Crushing		
Products	wt. %	Cr_2O_3, %	ε, %	wt. %	Cr_2O_3, %	ε, %
Concentrate	18.9	48.84	52.4	29.1	48.44	78.5
Middlings	33.2	19.49	36.7	12.2	11.48	7.8
Tailings	42.4	3.48	8.4	48.8	2.89	7.9
Slimes	5.5	8.12	2.5	9.9	10.57	5.8
Feed	100.0	17.62	100.0	100.0	17.95	100.0

As shown in Table 5, a great deal of chromite remained as "middling" using compressive breakage while higher amounts of chromite were found in concentrate after impact crushing. These results also suggested that liberation could well be obtained at higher size ranges (-1+0.5 mm), which becomes important for enrichment costs for future plant optimization.

At that point, the need for liberation degree analysis comes into prominence in order to correlate the cumulative recovery and grade of concentrates with these values and determine the type of breakage providing selectivity. In Table 6, the results of liberation degree analysis were shown along with the metal contents of products. Although similar contents were obtained for all fractions, particles were found to be slightly more liberated after impact crushing.

As shown in Table 6, impact crushing leads to higher liberation degrees while the content of concentrates were found in line with them. This finding showed that the breakage of chromite particles with impact crusher occurred through the liberation boundaries. Indeed, the differences between the values of the parameters with compression and impact crushing products were not marginal but significant. In literature, many papers have been devoted to the effect of different crushers on liberation degree (Hosten and Ozbay, 1998; Tomas et al., 1999; Nikolov et al. 2002; Stamboliadis, 2008). In these papers, the liberation characteristics of different types of materials like chromite, and limestone were studied in either experimental or theoretical studies. Beside different approaches given, the common point is that the liberation degree increases with finer size ranges. For instance, Hosten and Ozbay, 1998; stressed that liberation degree increases from 14.5 to 80.7 % at 60 MPa with piston die press from 0.500 mm to 0.150 mm, while it remains at 64.9 % with rod mill in the same size ranges. In a recent study, different breakage mechanisms as compressive bed and impact breakage was investigated by comparing their effects on liberation and their results showed that upon finer size distribution of compressive bed breakage mechanism, the liberation degree was relatively higher than impact breakage (Ozcan and Benzer, 2013). Similar findings were also shown in theoretical calculations that while the liberation degree was around 78 % for 0.300 mm particle size, it decreases to 50 % for 1 mm (Stamboliadis, 2008). If the liberation degrees of each size fraction are considered, it is interesting to note that while similar values were obtained at -0.5+0.212 and -0.212 mm size fractions, the difference for these values was around 7 % at -1+0.5 mm size range. These results can well be attributed to the breakage of particles from a close section of their liberation bound, which provided higher grade and recovery at that size range for impact breakage mechanism.

Table 6. Liberation degree and Cr_2O_3 % content of concentrates with respect to crushing types

	Compression Breakage		Impact Breakage	
Size Fraction, mm	Cr_2O_3, %	Lib. Deg., %	Cr_2O_3, %	Lib. Deg., %
-1+0.5	43.75	47.26	43.65	53.89
-0.5+0.2	50.29	71.67	51.44	72.37
-0.2	51.68	82.11	53.3	83.8

As mentioned above, similar studies were carried out for the comparison of breakage mechanisms with liberation degrees. However, only a few of them addressed the liberation degree along with shape factor (Hosten and Ozbay, 1998; Unland, G. 2007). To our knowledge, influence of crushing type on liberation degree and shape factor of particles along with their influences on enrichment conditions was not investigated in detail.

For this aim, Image analysis tests were carried out with all size fractions. In Fig. 3, representative pictures of each size fraction taken by binocular microscope at 2X magnification was shown. The results of these tests were given in Table 7.

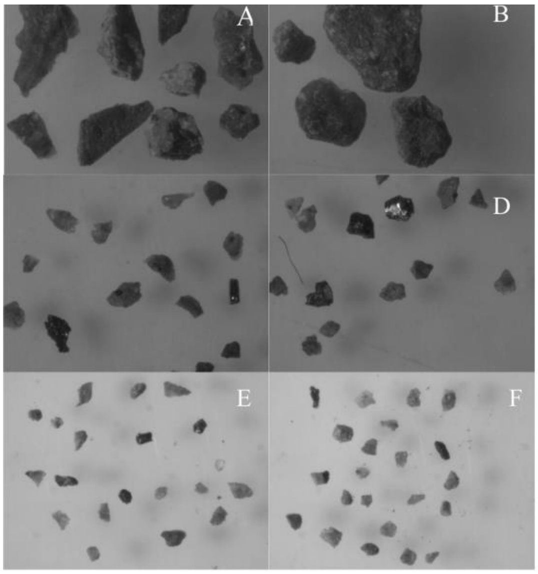

Fig. 3. Representative pictures of crushed chromite samples at different size ranges (A, C and E particles in 1+0.5; -0.5+0.212 and -0.212 mm size range with compressive breakage, B, D and F particles in 1+0.5; -0.5+0.212 and -0.212 mm size range with impact breakage)

Table 7. Shape factors and Cr_2O_3 % content of respective crushing types

	Compression Breakage		Impact Breakage	
Size Fraction, mm	Cr_2O_3, %	Roundness	Cr_2O_3, %	Roundness
-1+0.5	43.75	0.727	43.65	0.790
-0.5+0.2	50.29	0.722	51.44	0.778
-0.2	51.68	0.684	53.3	0.683

As it can be seen in Table 7, impact breakage resulted in more round particles in coarse size ranges as -1+0.5 and -0.5+0.212 mm while it became almost the same for each breakage type for -0.212 mm size fraction. Although very close values were obtained for coarse size ranges for both breakage types, the products of impact crusher were found relatively more spherical compared to compression breakage. Considering these values in each fraction shown in Tables 6 and 7, it is worth to note that if an evaluation made based on each particle size range, as the particles became more spherical, the recovery and liberation degree increases in -1+0.5 mm size fraction while it became independent of shape factor in finer size ranges.

The data given in Fig. 4 were utilized to better illustrate and also show the effects of both crushing mechanisms on liberation degree and shape factor along with their enrichment results. It can be clearly seen that for both crushing type, decreasing the size range of particles resulted in higher recoveries and liberation degrees along with higher angularity of the particles. In other words, as the liberation occurs in fine sizes, the shape of the particles became more angular and they disintegrate from each other close to their basic crystal structure as octahedral.

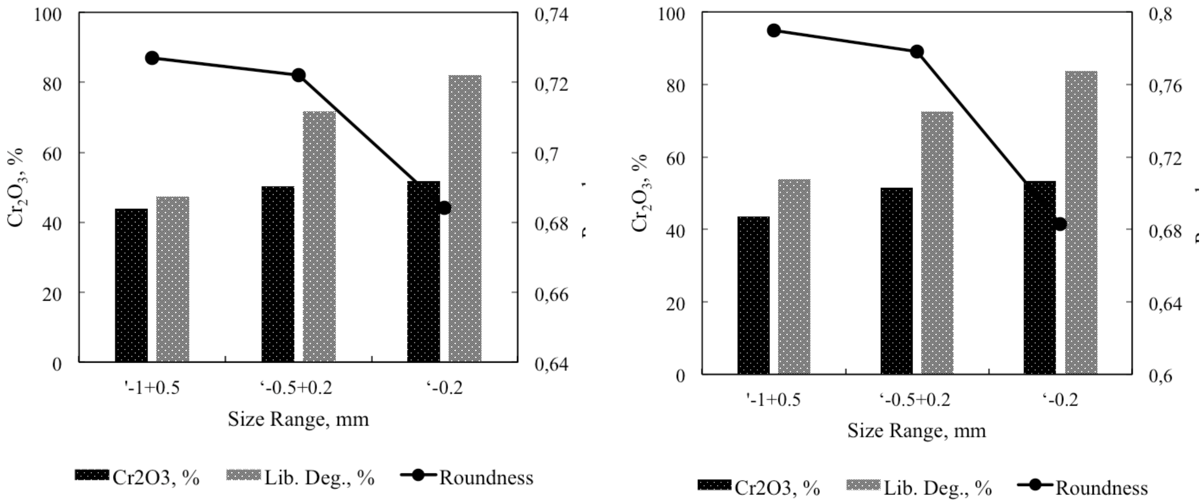

Fig. 4. The effects of different breakage mechanisms on liberation degree, roundness and metal recovery values of concentrates, (Left: Compression Breakage, Right: Impact Breakage)

4. Conclusions

In this study, a comparison was made between impact and compression crushing on both liberation degree and shape of particles along with the separation efficiency by shaking table. In the first method, a series of crushers including jaw + cone + roll crushers were adapted for compressive breakage whereas in the second method, only impact crusher was adapted for impact breakage. The crushed sample then screen out to different size ranges as -1+0.5 mm; -0.5+0.212 mm and -0.212 mm. Then liberation degree and morphological analysis were made for each fraction in order to find the relationship between grade and other features of particles as a function of breakage type. The results of these tests can be summarized as following:

- the valuable mineral chromite is more brittle compared to the associated gangue mineral. Therefore, it accumulates in finer sizes regardless of breakage type,

- the liberation degree analysis indicated that more liberated particles were obtained with impact crushing in all size ranges depending on disintegrating of valuable mineral from gangue minerals through their liberation boundaries,

- the overall results of this study showed that the usage of impact crushers produces more liberated particles during size reduction.

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