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GRINDING SIZE ESTIMATION AND BENEFICIATION STUDIES BASED ON SIMPLE PROPERTIES OF ORE COMPONENTS

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Abstract: In this study, the physical and mineralogical properties of three chromite ores taken from three different locations of Turkey (ore A, B, and C) were determined before the lab scale concentration studies. In this context, the mineralogical determination of mineral structure, liberation degree of valuable/gangue minerals, grindability properties (Bond work index, *BWI*), and size distributions of each ore were determined in detail. An empirical equation was derived based on the liberation size of Cr_2O_3, and the F_{80} and P_{80} values (80% passing size of feed and product in grinding, respectively) of the sample were obtained from the *BWI* tests for each ore. An estimation approach for the primary grinding size with the help of this equation was realized for each ore in the laboratory scale experiments. The results of first series of enrichment test for ore A showed that the chromite content of the concentrate (45% Cr_2O_3) was slightly lower depending on insufficient liberation size compared to ore B and ore C. On the other hand, due to the insufficient liberation in coarse size fractions, the middling with relatively high Cr_2O_3 content were obtained for ores B and C. After the optimization of the test conditions, saleable concentrates having 49–51% Cr_2O_3 grades with suitable chromite recoveries could be obtained for each type of ores. The empirical formula proposed in this research provided very suitable results (concentrates having saleable grades and higher metal recoveries) for the selection of primary grinding size of the ores. However, the results of the equation were limited to the ores used in these experimental studies. Therefore, it is recommended that the validity of this equation should be tested for other types of ores.

Keywords: *chromite ores, mineralogy, liberation, Bond work index, BWI, gravity concentration*

Introduction

Turkey is one of the leading countries in the World in chromite reserves as well as chromite production. Chromite ore deposits in Turkey are typically and mostly observed as lens shaped-massive, and nodular, but are also partly seen in tabular and

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schlieren form. As a result of intense tectonic activities, various ore types as massive, banded, leopard skin, and disseminated chromite in the host rocks are formed. The accompanying secondary minerals found in these deposits are mainly dunite, harsburgite, olivine, serpentine, and talc while magnesite and hematite varies in the minor amounts (Gunay and Colakoglu, 2015). Although most of chromite ore deposits have very similar features, the composition and liberation degree of chromite and gangue minerals have significant differences from one deposit to another related to the genesis of host rocks in different environments. These kind of mineral features are dictate varieties of individual processes for each ore types when beneficiation flow sheets are considered.

Chromite concentrates containing different chromite grades are produced in Turkey, varying from lumpy chromite to fine size concentrates. In concentration plants, gravity methods have often been used based on density differences between chromite and gangue minerals. Heavy medium separation and jigs in coarse sizes, spiral, shaking table, magnetic separators, multi gravity separators, and flotation in fine sizes (≈ 0.5 mm) are the well-known and widely acceptable methods (Burt, 1987; Guney et al., 2009).

The most common encountered problems in the plant trials are either disregarded mineral properties and over-grinding of materials. Both cases consume significant excess energy and valuable mineral losses in slime fractions. This is due to the incomplete basic pre-determination of the ore characteristics. In order to overcome undesirable aspects of processes, several basic pre-investigations for raw materials characteristics should be completed before the beginning of the process plant trials. Mineralogical structures of the ores, liberation degree of valuable/gangue minerals, grindability properties (Bond work index, *BWI*), and size distributions are the major parameters which can easily and simply be investigated in lab scale phases. However, several mechanical properties of ores like hardness, abrasion index, compressive strength, and elasticity modulus should also be investigated broadly in the extended pilot scale studies. Thereafter, the determination of these properties, most appropriate process steps, can be realized.

Comminution as a whole size reduction processes involves a sequence of crushing and grinding processes. Selection of the most appropriate comminution units and calculations of energy consumption can be estimated basing on Bond grindability index (*BWI*) results (Magdanilovic, 1989; Mosher and Tague, 2001; Tuzun, 2001; Deniz and Ozdag, 2003; Morrell, 2008). There are mainly two approaches to find out the energy consumption of a material ground from infinite size to 100 μm. The first one is Bond's grindability test which has been a widely accepted approach, and the second one is Hardgrove's index generally used for coal (Stamboliadis et al., 2011; Gamal, 2012). The Bond work index is regarded as size reduction resistance. It can therefore be presumed that the *BWI* is correlated to the physical and mechanical properties of materials (Mwanga et al., 2015). The number of grinding stages and necessity of intermediate grinding can also be predicted together with evaluating *BWI* values and liberation degrees of minerals (Ipek et al., 2005; Gamal, 2012). When the current chromium beneficiation plant data are analyzed, it is seen that mostly coarse sizes of middling obtained from enrichment stages should be subjected to the secondary grinding (intermediate grinding) for the case of *BWI* values of 12–13 kWh/t or higher. Moreover, the liberation degrees of chromite and gangue minerals provide also important information about the primary grinding size and fraction ratio of slimes during enrichment processes.

In this research, the basic physical and mineralogical properties of three chromite ores were examined before starting the lab scale concentration studies. Optimal process parameters for each ore were determined taking into account their basic ore characteristics. In this context, the mineralogical determination of mineral structure, liberation degree of valuable/gangue minerals, grindability properties (*BWI*), and size distributions of each ore were determined. Thereafter, the concentration tests using the gravity separation units (shaking table and Multi Gravity Separator-*MGS*) were carried out for the ground ores. Toward this aim, the relationship between basic features of ores and concentration data obtained in the lab scale studies were investigated (SMS, 2007; Mate, 2007; Teknomar, 2012).

Materials and methods

Materials

In the experimental studies, three chromite samples taken from different regions of Turkey were used. Each ore sample represented different mineralogical, physical, and chemical structures. These differences lead to significant variations of size reduction, size distribution, and in consequence the selection of enrichment process steps. The chemical properties of these ores are presented in Table 1.

Table 1. Chemical analysis of chromite ores

Assay (%)	ore *A*	ore *B*	ore *C*
Cr_2O_3	12.07	16.30	23.83
FeO	10.11	8.94	8.50
SiO_2	20.34	25.70	22.13
Al_2O_3	4.35	3.40	3.64
MgO	38.10	34.11	32.79
CaO	0.64	0.57	0.24
LOI	14.35	10.86	8.65

Methods

Prior to the enrichment tests, the size distribution studies on liberation size and chemical analysis of each sample were performed. In addition, mineralogical analysis of each ore on polished sections was carried out. Furthermore, the grindability feature of each ore was also determined by the *BWI* tests. Following determination of basic mineral properties, enrichment tests (shaking table and *MGS*) were carried out for each ore based on these findings.

Determination of ore characteristics

Determination of mineralogical properties

Polished sections were prepared from all of the characteristic samples taken from each run off-mine ore. The textural features, along with the data about liberation degrees of minerals structures were determined for both chromite and gangue minerals.

Ore A

The ore overall had a dunite type rock structure with chromite inclusions. Dunites were altered to become serpentines in various proportions. The chromite grains existed in a random pattern together with serpentine minerals filling micro-cracks in polished sections. It can be seen from Fig. 1 a-d that the chromite crystals were shattered and crashed by tectonic deformation, while the gangue minerals were primarily composed of olivine and serpantine group minerals. Magnetites were found as alteration products around the border lines or through the cracks of chromite grains. It is seen from Fig. 1 that the magnesite was seen through chromite crystal cracks and fewer inside the gaps of the rock. The average size of free and individual chromite grains was measured between 0.08 and 0.24 mm (Fig. 1 a-d).

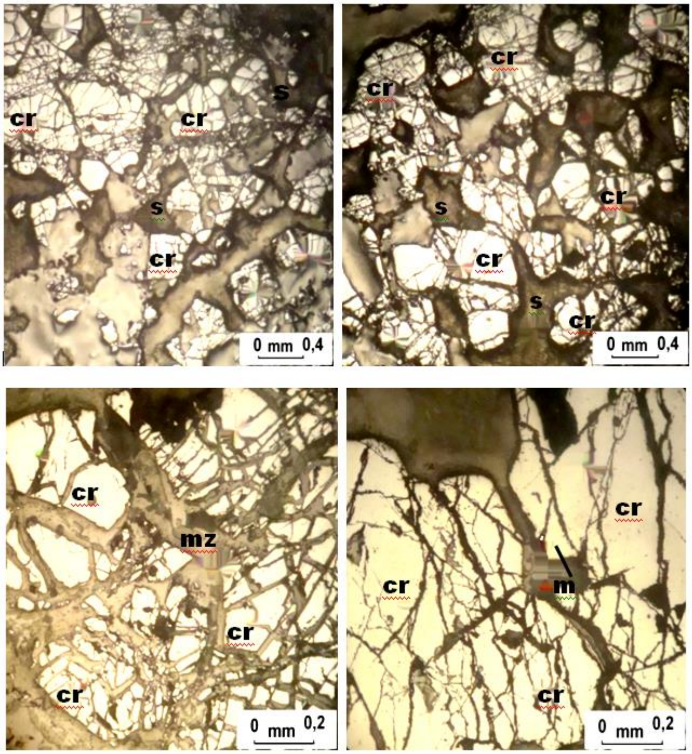

Fig. 1. Chromite grains (*cr*) are fractured with the impact of significant deformation (a–b) magnetite (*m*) and magnesite (*mz*) observed throughout the crystal cracks and boundaries (c–d)

Ore B

According to the polished section results, the chromite mineralization as dispersed textures were observed in serpentinised dunitic rocks, but banded type chromite structures were also found in lesser amounts. Chromite, olivine, pyroxene, chrysotile, antigorite, and in lesser amounts of magnetite, hematite and limonite as well as millerite and avaurite as trace nickel minerals were determined in the ore matrix. In general, chromite grains in the ore matrix were observed as in dispersed and partially cracked structures related to the deformation. Furthermore, it was observed that the cracks and fractures formed in host rock texture and borderlines of chromite grains were filled by chrysotile. Also, magnetite and hematite alterations in the borderline of chromite particles were observed partially. The average size of free and individual chromite grains was measured between 0.12 and 0.34 mm (Fig. 2 a-d).

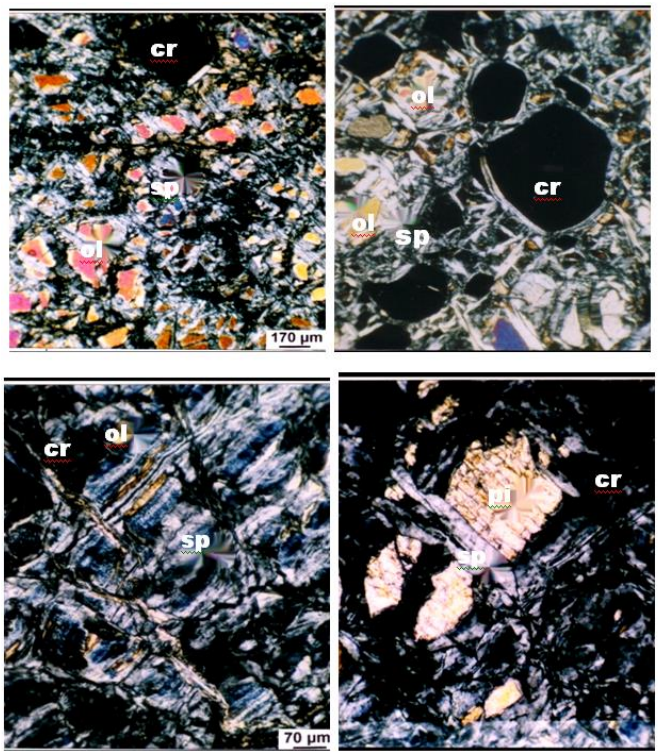

Fig. 2. Chromite (*cr*) and serpentine group minerals (*sp*) observed in dunitic rocks forming sieve texture (a-b); chromite (*cr*) grains together with pyroxene (*pi*) traces observed inside of serpentine group minerals (c-d)

Ore C

The examination of microscopic polished sections revealed that the chromite mineralization was observed as compact, banded, and scattered structures in dunitic rocks which expose slightly as serpentine. Chromite, olivine, pyroxene, brusite, magnesite, chrysotile, antigorite, and magnetite and hematite minerals with lesser amounts were found in the ore structure together with serpentine group minerals. Chromite was generally observed as circular-angular. Scattered and banded chromite grains within the ores were partially fractured as a result of deformation. The average size of free and individual chromite grains was measured between 0.09 and 0.30 mm (Fig. 3 a-d).

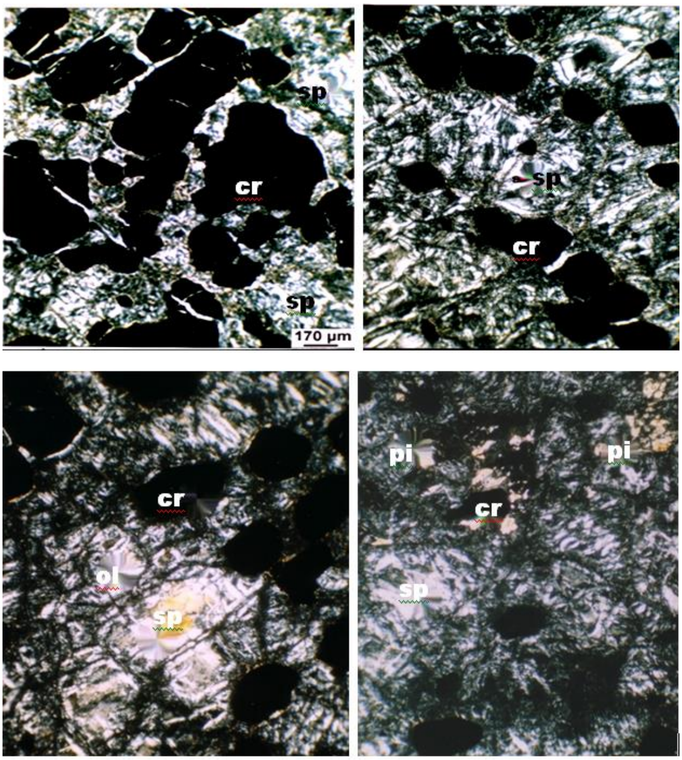

Fig. 3. Chromite (*cr*) and serpentinised (*sp*) olivine (*ol*) grains observed in dunitic composition of rocks (a-b) olivine (*ol*) and pyroxene (*pi*) turned into serpentine group minerals such as chrysotile and antigorite (*sp*) (c-d)

Determination of particle liberation size

Considering the mineralogical data for each ore, the samples were ground under 1 mm, classified, and the liberation degrees of chromite and gangue minerals were determined by the particle counting method using a binocular microscope. In this method, the liberation was determined taking into account the specific particle size in which 80% of the particles became liberated from each other. Thus, the findings of these tests also provided a basis for the selection of the optimum grinding size for the enrichment processes. The liberation degrees for each ore are shown in Fig. 4.

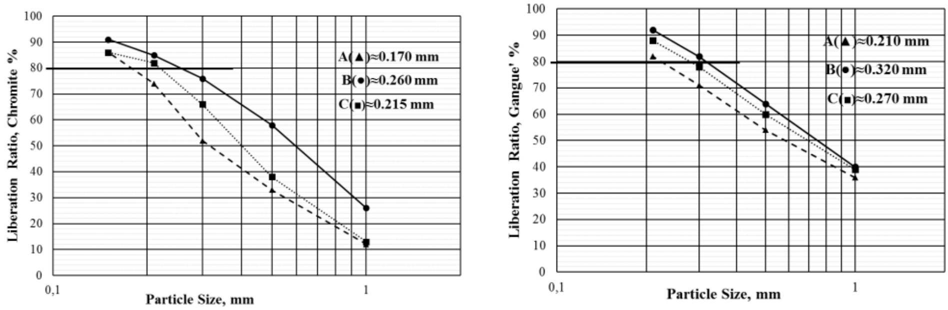

Fig. 4. Liberation degrees (80%) of individual chromite and gangue minerals

Determination of Bond work index

The Bond work index of chromite ores were determined using the standard Bond ball mill test (Mosher and Tague, 2001; Morrell, 2008). Work index (W_i) is found by simulating dry grinding in a closed circuit at 250% circulating load in a Bond ball mill. The work index is calculated by using the following empirical equation:

$$W_i = 49.1 \, / \, P_i^{0,23} \times G^{0,82} \times (10/\sqrt{P} - 10/\sqrt{F}) \text{ (kWh/Mg on dry basis)}$$

where W_i is the work index, expressing the resistance of the material to comminution. F and P is 80% passing sizes of feed and product, respectively. P_i, test sieve size, G (grindability), weights of the test sieve undersize per mill revolution. These values can also be used for energy calculations and basic data for the selection of grinding units. The values used in the Bond work index calculations; the G data for each chromite sample and the calculated work index values are presented in Tables 2 and 3, respectively.

Table 2. Bond work index test data of the chromite ores

ore A			ore B			ore C		
Number of rev. (R)	$P_B - F_B$	Grindability $P_B - F_B / R$ (G)	Number of rev. (R)	$P_B - F_B$	Grindability $P_B - F_B / R$ (G)	Number of rev. (R)	$P_B - F_B$	Grindability $P_B - F_B / R$ (G)
166	314.9	1.897	397	413.2	1.042	142	143.2	1.009
139	261.2	1.879	325	407.0	1.254	330	330.3	1.000
148	247.1	1.671	269	347.2	1.289	326	342.4	1.050
168	361.0	2.150	267	346.0	1.295	308	378.8	1.229
125	240.9	1.929	267	380.9	1.429	259	288.4	1.114
145	316.2	2.179	239	316.0	1.323	296	354.1	1.195
125	218.0	1.743	263	347.0	1.317	270	321.7	1.192
163	318.2	1.955	262	358.3	1.365	273	326.1	1.193
140	274.6	1.965	252	334.7	1.328	–	–	–
141	278.4	1.975	261	346.2	1.327	–	–	–

F_B – The weight of the material equivalent to 700 cm^3 volume
P_B – The weight of the ground material in Bond mill at minus 150 μm for each cycle
G – value of each ore was calculated based on median of bold numbers given on the table

Table 3. Calculated Bond work index (*BWI*) test values and results

BWI test values	ore A	ore B	ore C
G – g/rpm	1.965	1.327	1.193
P_i – µm	150	150	150
F_{80} – µm	2 150	2 380	1 750
P_{80} – µm	115	125	110
W_i – kWh/Mg (dry basis)	12.43	17.83	18.78
W_i – kWh/Mg (wet basis)	9.57	13.73	14.46

Results and discussion

The Bond work index values and the grinding time for size reduction under 1mm were interpreted for each ore along with the values of d_{50} and d_{80} (50% and 80% passing size of the material, respectively) of the ground material (Fig. 5). As expected, the grinding time increased with the increasing grindability index values of the ores. It is worth to note that these findings were all in accordance with the mineralogical and structural features of ores. For instance, the Bond work index for ore A was lower compared to other ores due to its over faulted and altered structure. In addition, the presence of quite high amounts of relatively softer gangue minerals such as serpentine and magnesite in ore A provided its easy grindability.

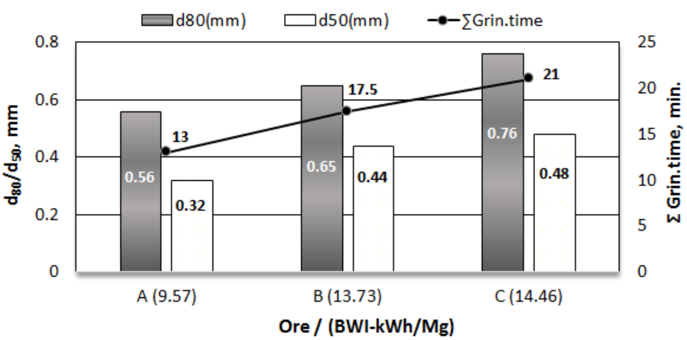

Fig. 5. Relationship between d_{80}/d_{50} and total grinding time of the ores

Table 4. The liberation size for chromite ore samples using different methods

Samples	Average liberation size for chromite particles (mm)	
	Mineralogical analysis	Particle counting method
ore A	0.160	0.170
ore B	0.230	0.260
ore C	0.200	0.215

The liberation size values determined with both mineralogical analysis and particle counting method by the binocular microscope are presented in Table 4. As it can be seen from Table 4, very close values were obtained for liberation sizes of chromite ores which indicates that both methods are convenient for the ores.

An estimation approach for selection of grinding size

As shown in the previous section, the liberation sizes for ores A, B, and C were determined as 0.170, 0.260, and 0.215 mm, respectively (Table 4). In this context, the slime ratios (–0.053 mm) of each ore upon grinding to these sizes increased up to 51%, 35%, and 25%, respectively. From an industrial view, the selection of these size ranges as the primary grinding size would be practically impossible. Considering these findings, an empirical equation was developed by evaluating the liberation size of chromite (LS-Cr_2O_3) and the F_{80} and P_{80} values obtained from the work index tests for each ore. With the help of this equation, an estimation approach for the first grinding size was obtained for each ore type on a laboratory scale. The proposed equation and the calculated grinding size for each ore are shown in Table 5. The results showed that the calculated grinding sizes of the ores with higher reliability were selected at -0.8 mm for ore A, and at -1 mm for the ores B and C.

Table 5. Data and results based on proposed grinding size calculation equation

Parameters	**ore A**	**ore B**	**ore C**
Liberation size of chromite, (LS-Cr_2O_3), mm	0.170	0.260	0.215
F_{80} – µm (*BWI* test)	2 150	2 380	1 750
P_{80} – µm (BWI test)	115	125	110
Proposed grinding size formula	F_{GS} (mm) = LS-$Cr_2O_3 \times (\sqrt{F_{80}} / \sqrt{P_{80}})$		
Estimated grinding size of ore (Calculated based on formula)	0.74 mm	1.13 mm	0.86 mm

Gravity concentration tests results

According to the proposed formula (shown in Table 5) within the scope of this research; ore A to –0.8 mm, ores B and C to –1 mm were ground and then subjected to the gravity concentration tests by using the shaking table and *MGS*. Evaluation of the data obtained from different size fraction along with the overall results of the concentration tests is summarized in Table 6.

For ore A ground to –0.8 mm, the chromite content of the concentrate product was 45%. This result could be attributed to the insufficient liberation ratio. The microscopic investigations of the products also showed that the optimum enrichment conditions could be obtained upon slightly decreasing the grinding size for this ore. On the other hand, the results of enrichment tests with ore C showed that middling products with relatively high chromite content of 21.72% was obtained at the coarser size fractions for the ore ground to -1 mm. These results can be explained with the higher grindability index and compact mineralogical structure of ore C. The results of the enrichment tests for ore B based on proposed equation were found very reasonable when the grinding size is considered.

Table 6. Gravity concentration test results of chromite ores

Product	ore A (–0.8 mm)			ore B (–1.0 mm)			ore C (–1.0 mm)		
	Weight (%)	Cr_2O_3 (%)	Recovery (%)	Weight (%)	Cr_2O_3 (%)	Recovery (%)	Weight (%)	Cr_2O_3 (%)	Recovery (%)
Concentrate	16.8	45.12	62.8	20.7	51.43	65.3	22.7	51.91	49.4
Middling	25.4	10.76	22.6	21.9	14.28	19.2	47.0	21.72	42.8
Tailings	43.5	2.47	8.9	45.6	3.87	10.8	21.2	5.10	4.6
Slime (-0.053 mm)	14.3	4.77	5.7	11.8	6.42	4.7	9.1	8.37	3.2
Total	100.0	12.07	100.0	100.0	16.30	100.0	100.0	23.83	100.0

In the following series of tests (second group), the conditions were optimized by the aforementioned findings. Therefore, the grinding size for ore A was decreased to ≈0.6 mm, and the middling of the tests with ores B and C were submitted to enrichment after re-grinding stages under 0.5 mm. The overall results of these series of tests are shown in Table 7. The results of second group of tests showed that saleable chromite concentrates (48.27%, 49.56%, 51.07% Cr_2O_3) could be obtained with suitable chromite recoveries (81.4%, 81.0%, and 86.3%) for each type of ore, respectively.

Table 7. Second group of tests gravity concentration test results

Product	ore A (–0.6 mm)			ore B (grinding of middling)			ore C (grinding of middling)		
	Weight (%)	Cr_2O_3 (%)	Recovery (%)	Weight (%)	Cr_2O_3 (%)	Recovery (%)	Weight (%)	Cr_2O_3 (%)	Recovery (%)
Concentrate	20.4	48.27	81.4	26.7	49.56	81.0	40.1	51.07	86.3
Tailings	61.7	2.58	13.1	58.9	3.59	13.0	45.1	4.32	8.1
Slime (–0.053 mm)	17.9	3.69	5.5	14.4	6.85	6.0	14.8	8.92	5.6
Total	100.0	12.10	100.0	100.0	16.33	100.0	100.0	23.75	100.0

Conclusions

In this study, basic structural and physical features of three different chromite ores were investigated. Within the scope of this research, simple estimation approaches using an empirical formula established in this study were proposed for primary grinding sizes of ores at lab scale beneficiation processes. Fundamental characteristics of the ores determined prior to enrichment studies at lab scale allow very quick and short way for the selection of the process parameters.

It was also observed that mineralogical properties and liberation degree/size analysis of the ores were well correlated with each other. On the other hand, the grindability characteristics of the ores were revealed using the *BWI* test values. A simple empirical formula involving liberation size data of the ores and *BWI* test outputs was proposed. This formula yielded very suitable results (concentrates having saleable grades and higher recoveries) during the selection of primary grinding size of the ores at lab scale studies. However; the results of equation were restricted to the ores used in these experimental studies. Therefore, it is recommended that the validity of this equation should be tested for other types of ores.

An optimum grinding size for each ore was selected in the second series of experiments after evaluating the basic mineral characteristics including mineralogical studies, liberation size analysis, size distribution of the ores and *BWI* data. The results of the second series of tests clearly showed that the application of the suggested equation to test conditions, saleable chromite concentrates ($\geq$ 48% Cr_2O_3) with suitable metal recoveries ($\geq$ 80% Cr_2O_3 recovery) could be successfully obtained.

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