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Relationships between comminution and chemical, petrographic and mineralogical properties of ores, and their effect on concentration

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Abstract: Especially in terms of energy costs, data on chemical, petrographical, and mineralogical analyses of ores or minerals can provide very important information for their production in the desired size distribution. Therefore, suitable crushing and grinding machines can be selected, taking into account the data affecting the comminution such as grain size, texture, metamorphism, and mineral or element contents. However, in most mineral processing plants, these data are rarely used to understand the response of ores or minerals to comminution. Analysis of the relationships between the chemistry, petrography, and mineralogy of ores and the breakage mechanism during crushing or grinding has been the subject of researchers in the comminution field in recent years. This study is a review of studies done so far on the relationships between the comminution and the chemical, petrographic, and mineralogical properties of different ores and minerals, and their effect on concentration.

Keywords: ores, minerals, comminution, chemical properties, petrographic-mineralogical properties

1. Introduction

The comminution is a process involving a series of crushing and grinding operations using different types of equipment with different comminution mechanisms such as abrasion, compression, or impact. This process is applied for three main purposes: Liberation, size reduction down to suitable feed size of applied concentration process, and preparation of ores having suitable size distribution according to market specifications. Mineral processing is a physical process. Therefore, minerals should be liberated sufficiently prior to concentration. Feed particle size distribution should also be taken into consideration together with liberation rate since concentration processes have distinct particle size limitations. Comminuted ore or rock may also directly be used in related fields depending on size distribution. For example, filler applications require ultra-finely ground minerals such as calcite and barite, etc. (e.g., d_{90} -5 µm), while crushed ore down to aggregate size (below 25 mm) is used in road construction.

The operating cost of a mineral processing plant mainly depends on the comminution process as it consumes about 50% of the total power consumption. Therefore, ore characterization to determine crushability and grindability has a key role. Laboratory-scale comminution tests are performed for this aim. The energy-size reduction relationship is established by many laboratory tests developed to aid in the characteristics of comminution equipment, circuit design, and optimization. Size reduction-based tests such as rock mechanics (the Uniaxial Compressive Test (UCS), the point load test (Is), the Brazilian test (ITS), the impact strength test (ISI), Los Angles abrasion test (LA), the Schmidt Hardness (SH) test and the ultrasonic tests, etc.), single-particle (the Drop Weight Test, Ultra-Fast Load Cell Test, Twin Pendulum Test, etc.), and grindability methods (the Bond grindability index, the Hardgrove grindability index, etc.) are commonly used to determine the breakage behavior of rock (ore or mineral).

Previously, many researchers thought that fracturing in comminution machines should be studied on a single-particle. They indicate that the strength of the rock is very important in determining the behavior of the rock under an applied force and that this strength is controlled by parameters such as mineral types in the rock, spacing between minerals, texture properties of the rock (King, 2001; Unland and Szczelina, 2004). However, most existing rock breakage tests have shown that they do not meet established criteria for proper mineral processing. The Bond mill and the Drop Weight tests were found

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to be the most validated by most researchers. However, the characterization of rock strength parameters is not a standard for comminution. Furthermore, the mechanical properties of materials obtained by single-particle fracture are not sufficient to explain the comminution phenomenon alone. Many researchers have also advocated the view that the comminution of material should be determined by laboratory test equipment that uses the same comminution mechanisms as industrial crushers and grinders. The comminution theories always assume that the material is brittle and that there is a relationship between the particle size of the ground product and the energy expended continuously. This means that the energy will be spent entirely on the forces (compression, impact, attrition, etc.) in the breakage process (Tavares and King, 1998).

Over the years, it has been revealed that the comminution theories (Rittinger, Kick, Bond, etc.) put forward by many researchers over the years can be valid in different size ranges (Hukki, 1961). Among the comminution theories, the best known is the Bond theory (Bond, 1952), and it has been the most widely accepted and applied for the design and optimization of grinding circuits. However, it is compulsory to determine the grindability value (G_{bg}) required for the Bond method. However, the Bond grindability value leads many researchers to find easier and simpler methods because of the need for a special mill with set ball-charge distribution, speed, and dimensions, as well as being extremely tiring and requiring a long time to test (Deniz et al., 1996; Deniz and Ozdag, 2003).

In recent years, comminution efficiency has significantly increased as a result of the development of new models, providing the least energy consumption by adjusting the operating variables of current comminution machines. Additionally, less energy-consuming novel comminution equipment designs have started to be applied in crushing and grinding circuits (Deniz, 2004a). Previously, the use of the matrix model in the comminution process was recommended by many researchers, but recently, the kinetic model has been suggested for both laboratory and industrial-scale applications. In the kinetic model, comminution is considered to be an ongoing process in which the breakage rate of the particle size is proportional to the mass of that size (Deniz and Onur, 2002). Austin et al. (1984) discussed the advantages of the kinetic model both in their well-known books and in many articles and stated that it would give more valid results to simulate laboratory grinding test data in industrial-scale mills.

The primary strategy for efficient comminution is to choose the appropriate comminution devices for each material. While the choice of a suitable comminution device is important, the basic mechanism understanding of the comminution process should also be taken into account. Most of the research on comminution so far has been on approaches to having an efficient comminution process by addressing the breaking and energy consumption in the comminution system. In many studies, mechanical stress is one of the factors controlling ore or rock fracture. However, heterogeneity in ores is very important in comminution, and the comminution response of a heterogeneous ore will be affected by the petrographic and mineralogical properties of the ores as well as the properties of mechanical stresses applied in the mill. The ore texture is associated with the natural properties of the mineral particle, while the mechanical stresses are associated with the comminution environment.

Comminution is a complex process governed in part by the mineral size, the chemistry of ore or minerals, and the nature of the particle crystal (attachment and crack structure). Therefore, it is necessary to consider the existing comminution circuit with respect to the chemical, petrographical, and mineralogical properties of ores and incorporate these ore properties in the comminution design of the comminution devices to optimize the comminution circuits. These two strategies require a better understanding of comminution by analyzing fracture fundamentals, correlating ore micro properties with process micro-dynamic and micro-static events.

A detailed study of both the mineral chemistry and mineralogy of ores is needed to optimize crushers and grinders. Ideally, it should be considered along with other important factors, such as the liberation, chemistry, and texture of the ore, in the evaluation of cracks in the ore as a result of comminution. The process improvement approach is then integrated, linking together the various contributing factors such as the type of comminution devices, and their capacity.

The purpose of this article is to show how chemistry, petrography, and mineralogy can be used to add value to comminution processes and why they are vital to the future of comminution. This article focuses on the benefits of chemistry, petrography, and mineralogy to improve comminution performance for different ores or minerals. A range of important aspects of chemistry, petrography, and mineralogy has been selected for discussion here, along with example case studies and references. These include the relationship with each other characterization of minerals and measurement of comminution performance; optimizing size dealing with variable, complex, and problematic ores or minerals; the importance of collaborative multidisciplinary teams (chemist, mineralogist, etc.) is also discussed.

2. Determination of chemical, petrographical, and mineralogical properties of ores

Chemical, petrographic and mineralogical properties of ores are very important characteristics that must be evaluated at various stages of mineral engineering, including energy consumption in the comminution circuits, liberation state of minerals, choice of concentration method, and plant performance. The success of the process from comminution to separation stages implies knowledge of the minerals themselves. The most key attributes to be considered include the content of the minerals in the ore, the mineral grain sizes, texture, and bond associations with each other (Graca et al., 2015).

A better understanding of the chemical, petrographical, and mineralogical characteristics of the ore is needed as a way to maximize the value of the ore. In recent years, some researchers have aimed to link these characteristics of the ore with its comminution and beneficiation performance (Deniz, 2004a; Deniz, 2004b; Kekec et al., 2006; Deniz et al., 2007; Velazques, et al., 2008; Deniz, 2011; Deniz et al., 2011; Deniz, 2012; Bradshaw, 2014; Tungpalan et al., 2015; Wang, 2015; Yildirim, 2016; Mwanga et al., 2017; Graca et al., 2015; Shalchian et al. 2017; Diaz et al., 2018 and 2019; Liu et al., 2018; Togersena et al., 2018; Diaz et al., 2019; Rincon et al., 2019; Oledele et al., 2021; Schmitt, 2021; Semsari Parapari, 2021; Deniz, 2022a).

Techniques involving detailed polarized and optic microscopy, Scanning Electron Microscope (SEM), or Quantitative Evaluation of minerals by SEM (QEMSCAN) aided by image analysis are important tools that can reveal the texture feature of an ore or mineral. On the other hand, there are few studies examining the relationships between mineralogical and chemical properties of ores or minerals and their crushing and grinding responses (Deniz, 2004b; Deniz et al., 2007; Velazques et al., 2008; Deniz, 2011; Deniz et al., 2011; Deniz, 2012; Deniz, 2013; Yildirim, 2016; Mwanga et al., 2017; Togersena et al., 2018; Diaz et al., 2019; Deniz, 2022a). Describing the petrographic and mineralogical properties and chemical composition of ores or minerals will assist in the selection and mathematical modeling of crushers and grinders and shed light on explaining the comminution behavior of the particles. The benefit of describing these features of minerals or ores also helps us to analyze non-normalizable breakage behavior (King, 2001).

With the development of mineralogical techniques in recent years, although most instruments will be used by highly experienced chemists and mineralogists, chemistry, and mineralogy expertise will not be necessary with the timely introduction of automated systems. Therefore, mining engineers will need to work at a different level to make a significant contribution to ore processing.

It is important to carry out quantitative and qualitative analyses of content oxides in ores. While the X-Ray diffraction (XRD) and the quantitative X-Ray diffraction (QXRD) methods are mostly used in the determination of mineral types and their amounts purposes, element content analyses of minerals are carried out using tools such as Atomic Absorption Spectrometer (AAS), X-Ray fluorescence (XRF), and Inductive Coupled Plasma–Mass Spectrometer (ICP-MS), etc.

An XRF measurement analyzer is the most widely used method today, which can easily and quickly detect the quantitative mineral content of ore or rocks. While X-ray diffraction (XRD) is the fastest and best tool for identifying and quantifying the turnaround time of minerals found in ores or minerals, it is seen that the analysis interpretations in the mineral content determination are very little examined, especially considering that it is highly influenced by personal experience. The reason for this situation is that even the same mineral can present structural differences under different physical conditions.

When the literature is examined, it is seen a lot of work on the determination of mineral content and crystal system analysis. Even, Cullity & Stock (2001) and Grimmer (2016) have written very detailed books on the technique of XRD. In their books, they studied in detail the arrays and properties of crystal systems, determination of crystal structures, XRD in different crystal systems, and peak analysis, but the mineral content analysis is little involved in the mineral engineering field.

Several measurement systems based on the application of SEM, QEMSCAN, petrographical, and mineralogical technology on polished and thinned section samples have been developed to basic parameters used for process plant design and optimization. Moreover, the image-based numerical modeling method is an important tool in mineral processing in terms of revealing the ore or rock fracture process and ore texture. It has also become a very useful technique with a wide range of applications, often alone or in combination with other techniques (such as microscopy).

First of all, microscopy (polarization or optical microscopy) is still one of the most useful techniques today and seems to continue in the future. This instrument provides important information about the ore or rock through the qualitative observation of mineralogical composition and textural properties. Some mineralogical and petrographic properties of ore or mineral can be resolved by microscopy without the need for analytical tools such as XRD, SEM, and QEMSCAN.

The developed methods have been simulated for inclusion in petrographic, mineralogical, and chemical databases of the ore or mineral to improve comminution and concentration performance. In addition, in recent years, all these features have been tried to be explained with statistical correlations.

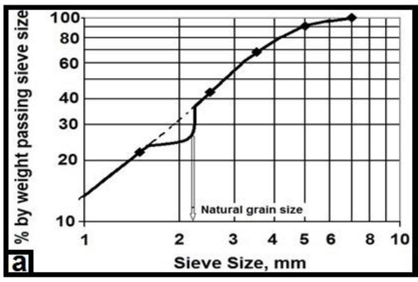
3. Effect of chemical, petrographical, and mineralogical properties of ores on the comminution

In the selection of the most suitable crusher and grinding machine for a mineral or ore, both giving the desired product size distribution and giving the least energy consumption are taken into consideration. However, Bradshaw (2014) suggested "process mineralogy" approach as a bridge between their comminution properties with mineralogical and petrographical properties of ore, and indicated that these properties of the ore would assist in designing a more realistic process flow sheet or modifying an existing plant design. He also said that the petrographic, mineralogical, and chemical properties of ores or minerals will have significant effects on mineral processing and variation in particle size, resulting in significantly different power consumptions at various comminution stages.

Although it is known that the mechanical, chemical and mineralogical properties of materials have a strong effect on comminution, there are limited works on this issue in the literature. Berry et al. (1984) investigated the correlations between jaw crusher performance and materials properties. They carried out porosity tests, strength tests, and elastic modulus tests and found some correlations between the materials' properties and the performance of the crusher. Strohmayr et al. (1998) found that there was an inverse relationship between the magnetite content of the iron ore and the hardness of the rock. Therefore, they stated that a negative correlation also should be expected between magnetic susceptibility and the Bond work index (W_i). Kekec et al. (2006) investigated the effects on the comminution behaviors of the grain size distribution and textural properties of the materials and obtained some relationships with statistical methods.

Differences in the comminution behavior of phases, that already exist due to the nature of the mineral phases of an ore, cause "selective fracturing" during size reduction, which may be demonstrated by sieve analyses. Crystal materials break more uniformly due to the fracture stress being more evenly distributed than amorphous materials during the comminution. Therefore, the comminution of amorphous materials due to the nature of the material affects the size of the product to some extent. Materials that consist of more than one grain, have porous structure, exhibit fibrous or lamellar formation, or particles of one material embedded in the matrix of another, especially in cases where the force applied by the comminution equipment is the impact force (impact crusher, autogenous mill, etc.) that is, the mineralogical, petrographic, and structural properties as nature of the materials affect the particle size distribution. Materials having this disposition are said to have a *natural grain size* (Lowrison, 1974). The occurrence of natural grain size can be detected in a Gaudin-Schuhmann plot (log-log plot) in the cumulative % passing (undersize) versus the particle size as seen in Fig. 1[a].

Additionally, the passage of rock containing mixture minerals through comminution equipment that applied impact force can cause separation of the grains of the different minerals with a degree of precision, i.e., it can be regularly collected into a rich size fraction. Therefore, this case will affect the success of a subsequent concentration process such as flotation, gravity separation, etc. For example, the different dunite rocks, named A, B, and C, containing chromite, olivine, and serpentine minerals, sieve analyzes were made after crushing in an impact crusher, and the results of the analysis according to the chromite content (as Cr_2O_3, %) in each size fraction were given in Fig. 1[b]. As shown in Fig. 1[b], sample-A reached the highest Cr_2O_3 grade below 75 µm, which is the lowest dimension, while sample-C, on the contrary, reached the least Cr_2O_3 grade below 75 µm. In sample-B, Cr_2O_3 grades close to each



b

Sieve Size (μm)	A Cr_2O_3, %	B Cr_2O_3, %	C Cr_2O_3, %
-2360+1180	16,34	24,76	32,45
-1180+600	18,56	26,58	30,23
-600+300	22,81	22,51	28,25
-300+150	28,42	23,75	23,68
-150+75	33,65	25,82	19,34
-75	38,27	24,43	11,23

Fig. 1. View of natural grain size [a] (from Lowrison, 1974), and the distribution of chromite (Cr_2O_3, %) grade in the sieve analysis results of three different dunite rocks after passing through an impact crusher [b]

other were obtained in all sieve fractions. This situation is entirely due to the different mineralogical and petrographic characteristics of the dunite rocks. Therefore, the economic advantages of concentration methods can be enormous, as materials with a natural grain size will affect separation.

As mentioned before, the chemical, petrographic, and mineralogical properties of ores would be expected to affect the grindability of the ore by non-random breakage in the comminution of ores of a certain size. Therefore, knowing in advance the possible differences in grindability can enable comminution and concentration circuits to operate with better performance. The mineralogical, petrographic properties, and chemical contents of all minerals or ores are often different. When investigating the comminution properties of rocks (ores or minerals) it should be essential to investigate their texture and chemical properties in determining their grindability or their crushability. Many researchers argue that the comminution of rocks can affect their mineralogical characteristics such as texture (grain size and grain shape), fabric (porosity and arrangement of minerals), metamorphism, degree of interpenetration, contact type, and mineralogy composition. However, there is not much information about the effect of petrographical and mineralogical properties in mineral processing operations because these properties are difficult to incorporate into the plant circuit design and relevant information can be treated as categorical variables rather than numerical variables.

Wiegel & Li (1967), King & Schneider (1998), and Gay (2004b) discussed the effects on the comminution properties of the modal composition derived from the petrographic, mineralogical properties of a given rock (ore or mineral), however, they found the findings in the material's model composition too complex to translate practically into a plant circuit design. Before attempting to model the comminution properties of a particular ore, the lack of knowledge about the effects of grain size, mineral grade, and mineral composition, among ore control parameters, on the breakage rate and liberation must be addressed. Petruk (2000) reported that all textural properties of the ore affect both its breakage and liberation, and hence the concentration of the ore, and he said that the main properties affecting them are mineral grain size and bond between grains.

3.1. Effect of chemical, petrographical, and mineralogical properties of ores on the crushing

Almost all crushers break ores or minerals by fracture propagation caused by compression, shear, and impact forces. In 1921, the first theoretical foundations of fracture mechanics began when Griffith (1921) related the propagation of fracture in a material with already existing cracks or defects. Later, Irwin (1957) suggested that fracture in the material propagates when the stress intensity, which varies for each material, approaches a critical value.

Fine-grained rocks, such as limestone, develop very flat needle-shaped fractures under pressure that fractures spread and suddenly form without interacting with each other. However, marbles with the same mineralogical properties as limestone but with coarse and weakly bonded grains develop multiple macroscopic fractures clustered in shear bands. Also, since the plastic deformation feature of calcite grains in marble decreases the stress intensity at the crack tip, crack propagation and the crack expands laterally are prevented. As a result, the size and mechanical properties of calcite create two very different fracture mechanisms both marble and limestone. This is why marbles break very differently than limestones because of their already existing cracks (Guimaraes et al., 2007).

Guimaraes et al. (2007) investigated oxide content versus fracture values of granite rocks in a Los Angeles (LA) abrasion device, which resembles a kind of ball mill, and found that quartz enhances rock degradation, possibly because it fractures weaker minerals other than quartz. Conversely, they stated that the existence of biotite (Fe_2O_3) in the rock decreased the amount of abrasion, and they attributed this to a cushioning effect that probably reduces impact stresses and abrasions.

Lois-Morelas et al. (2020) presented a single-particle breakage test to understand the differences in breakage properties of rocks and properties related to their texture. They selected for analysis four quartz-monzonite samples with different textural and mineralogical characteristics (different alteration properties). Each particle was broken using the Short Impact Load Cell, which consists of a long steel rod equipped with strain gauges on which a single particle is placed and impacted by a falling steel ball. They reported that the breakage energy can be interpreted as the signature energy of the rock in comminution as it is directly associated with its geological properties and is not coupled with machine properties. Also, they indicated that fracture force decreases as the hydrolytic alteration increases, while deformation of the particle usually increases with the alteration.

Papadopoulos et al. (1995) and Isık (2007) stated that one of the most important parameters affecting the mechanical properties of gypsum rocks is the texture (grain size and shape) and the other is the interlocking feature of gypsum grains. In addition, Adriani and Walsh (2002) stated that texture, such as geometry and topology of the pore network, grain shape, granulometry, and packing of calcarenites, affects the shear strength of calcretes of carbonate rocks. In another study, Ajalloeian et al. (2020) performed multiple regression analyses between the *UCS*, the *ITS*, and the Schmidt Hardness (*SH*) with petrographic properties of granitic rocks and established important and valid relationships by emphasizing the effect of quartz/feldspar ratio and grain size. Similarly, Askaripour et al. (2022) investigated the effects on the rock mechanical parameters of anisotropy, grain size, grain shape, and mineral composition. They indicate that the main influence on the rock mechanical parameters lies in changes in the feldspar and quartz content, and said that grain size and porosity play a more important role in fracture properties than mineral composition.

Deniz (2011) carried out dynamic crushing tests of three different limestones under the same conditions in a laboratory-type impact crusher. He found that the limestone type plays a very important role in comminution and the limestone sample with the lowest CaO content is more breakable than the other samples.

3.2. Effect of chemical, petrographical, and mineralogical properties of ores on the grinding

The general problem with comminution theories and models is that they assume that breakage is not affected by the type or texture properties of minerals present in ores and rocks and that ores or rocks break randomly in comminution. However, there is a non-random breakage that affects the comminution of ores or rocks with minerals of different brittleness. This may occur with factors such as selective breakage of minerals with a higher probability of crack branching, breakage around mineral boundaries, and detachment of the grains in composition and/or texture (Diaz et al., 2019). Although a macro-scale relationship can be established between the grindability of rocks and their mineralogical and petrographic properties, it is difficult and complex to reveal the relationships at the micro-scale. If relationships can be established between micro-scale textural properties and comminution properties, this will be crucial for a better understanding of comminution processes, given that, for example, a very large calcite deposit may have geological variability. Therefore, the grindability indices of such a large calcite deposit can shed light on the average grindability characteristics of the entire calcite sector.

Deniz et al. (2007) investigated the comparison of the comminution properties of two different groups of chromite ores in a laboratory ball mill and presented the relationships between the kinetic breakage parameter values and the Bond grindability values of two different chromite ores. As a result of the investigation of the thin and polish section; Group-I samples have containing chromite and serpentine minerals, while Group-II samples have containing olivine and chromite. The experimental values showed that grinding was not faster according to kinetic breakage parameters for samples as the value of the Bond grindability (G_{bg}) increases. The reason for this state, the chromite samples have different mineralogical properties. On the other hand, they showed that the first-order refractive constant (a_T) changes with chromite content (Cr_2O_3, %), as seen in Fig. 2[a].

Deniz (2004b), in his grinding study on pumices, namely the Gelincik and the Karakaya, which have two different chemical and mineralogical properties, has shown that the upper dimensions are easier to

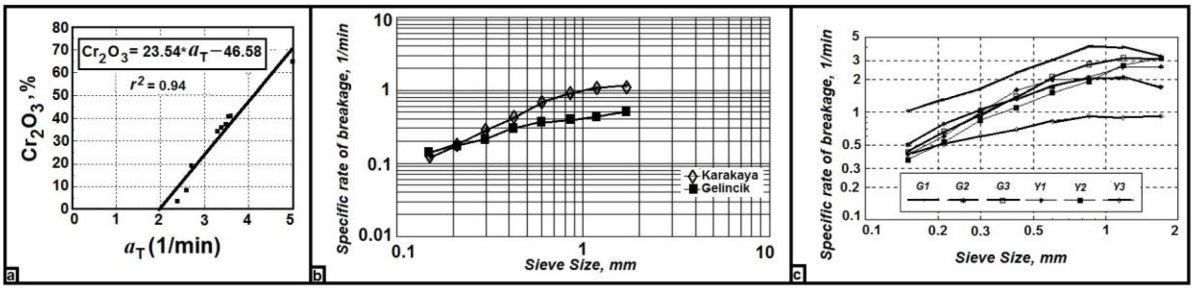
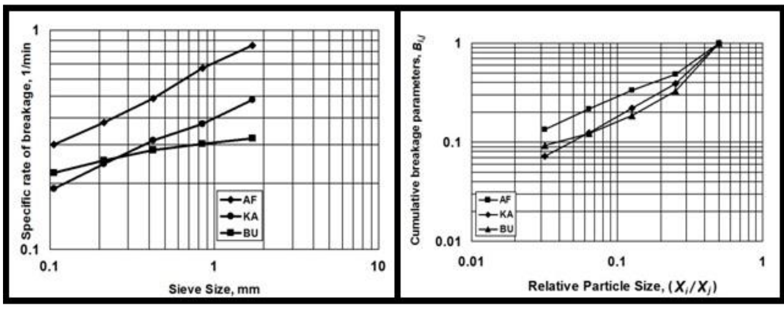


Fig. 2. The first-order refractive constant (a_T) changes with chromite content [a] (from Deniz et al., 2007), the specific rates of breakage of two different pumice [b] (from Deniz, 2004b), and six different limestones [b] (from Deniz, 2004a) with grinding in ball mill

break because Karakaya pumice has more porosity than Gelincik pumice (Fig. 2[b]). On the other hand, from the mineralogical tests, it was found that Karakaya pumice has more abrasive properties than Gelincik pumice; therefore, Karakaya pumice gave a lower production rate of fines than Gelincik pumice.

Deniz (2004a) compared the kinetic breakage parameters for six different limestones in a ball mill and found that the high MgO content, determined from the chemical analysis of the limestone samples, had a significant reducing effect on the specific rate of breakage values (like Y3 in Figure 2[c]).

Noh and Lee (2007) conducted a study to reveal that the crystal size distribution, degree of cleavage development, crystal morphology, and texture in limestone play important roles as control factors influencing grinding effects and powder properties. They particularly emphasized that calcite cleavage is the most important factor to control the properties and quality of calcite powder, and therefore special ore properties such as higher crystallinity and conspicuous cleavage development are required for high Ca limestones to be used as fillers and extenders. In a study supporting this, Deniz (2022a) made a comparison of the kinetic model functions (S_i and $B_{i,j}$) parameters of three different calcites in a Hardgrove mill and the results were given in Fig. 3. As a result of chemical and mineralogical investigations of samples, he stated that there were differences in mineral grain sizes, oxide contents, and textural and alteration properties of calcite. Particularly in mineralogical studies, he stated that the cleavage surfaces of growing calcite crystals become evident by re-crystallization processes and that calcite grains undergoing complete metamorphism have a significant effect on the kinetic breakage parameters, and thus metamorphism facilitated the grinding of the sample. On the other hand, he stated that the presence of dolomite, which was determined from chemical analysis and XRD results, made the grinding process difficult.



Chemical composites of calcite samples used in the experiments

Oxides (%)	Calcite-AF	Calcite-BU	Calcite-KA
CaO	54.90	55.47	40.50
MgO	0.26	0.29	17.33
Al_2O_3	0.14	0.13	0.12
SiO_2	0.19	0.00	0.00
Fe_2O_3	0.13	0.02	0.05
SO_3	0.13	0.03	0.04
Na_2O	0.00	0.05	0.11
K_2O	0.04	0.00	0.00
Loss on ignition	43.21	42.85	46.03

Fig. 3. The chemical composites, the specific rate of breakage (S_i), and the cumulative breakage parameters (B_{ij}) for calcites with three different chemical and mineralogical properties in a Hardgrove mill (from Deniz, 2022a)

Velázquez et al. (2008) conducted a study on the effect of different mixtures of serpentine and limonite minerals found in oxidized Ni-Co ores on the grinding process (in terms of the Bond work index, the breakage, and selection functions). However, they found that the kinetic grinding functions of each mineral component were not dependent on the mineral content in the sample, as seen in Fig. 4 [a, b]. On the other hand, they found that the Bond work index values of serpentine minerals alone are similar to the values obtained when ground in a mixture (as seen in Fig. 4[c]). It is understood from this

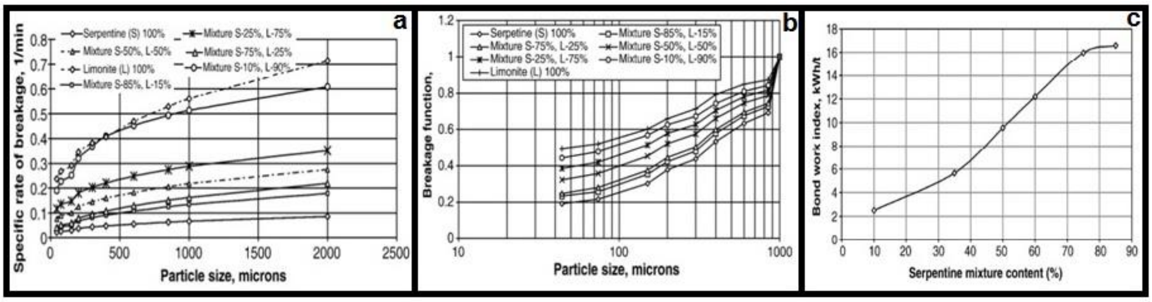


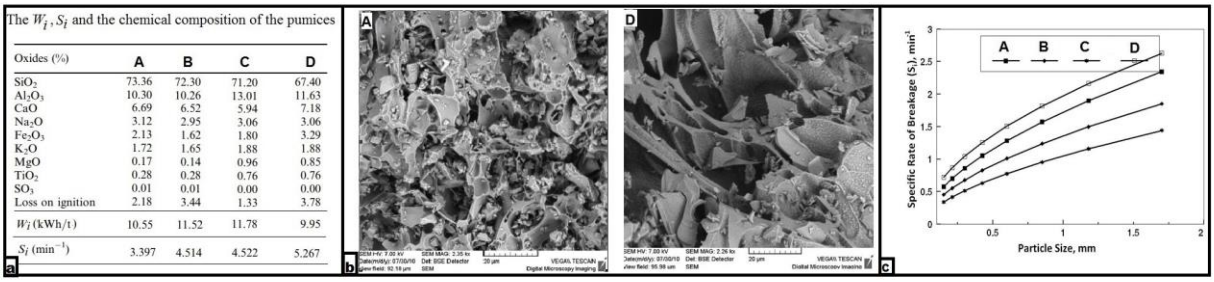
Fig. 4. The specific rate of breakage function [a] and breakage function [b] and variation of the Bond work index values of Ni-Co ores with different serpentine and limonite contents (from Velázquez et al., 2008)

that the approach that best characterizes grinding is the kinetic grinding parameters rather than grindability data.

Togersen et al. (2018) investigated whether ore mineralogy and texture properties of six different iron ores could be associated with both the Schmidt hardness and the grindability values (by autogenous milling test). According to the test results, finer-grained ores with flat grain boundaries increased the surface hardness, while finer-grained ores, with flat-grain boundaries, which are high iron grade, decreased grindability. In addition, they said that even the magnetic separation performance of the ore can be evaluated from the important relationships found between ore mineralogy, texture, surface hardness, and grindability parameters.

Vernik et al. (1993), Li & Aubertin (2003), and Basu & Mishra (2014) investigated the effect of porosity on the strength of different materials, and they proposed that increased porosity in the material will reduce that material's strength. Similarly, Deniz et al. (2011) emphasized that the porosity properties of the materials changed the grinding, and pumice samples with different mineralogical and morphological properties gave different specific rates of breakage.

In addition, Deniz (2013) investigated the dry grinding behavior of four different pumices in terms of both the Bond work indexes and kinetic breakage parameters. As seen in Fig. 5[a], he stated that while the high SiO_2 content of the pumice samples showed a negative effect on the specific rates of breakage (S_i), the effect on the Bond grindability could not be determined exactly. Since the D-pumice sample has hypo-crystalline and vitrophyric texture, i.e. more porous with larger pore lengths (Fig. 5[b]), than the other samples (for example; A-pumice), the specific rates of breakage (S_i), as seen in Fig. 5[c], was found higher. He also stated that the pore diameter would be larger at large particle sizes and thus breakage would be faster, while the breakage rates would converge at fine particle sizes because the porosity would be lost.


The W_i, S_i and the chemical composition of the pumices

Oxides (%)	A	B	C	D
SiO_2	73.36	72.30	71.20	67.40
Al_2O_3	10.30	10.26	13.01	11.63
CaO	6.69	6.52	5.94	7.18
Na_2O	3.12	2.95	3.06	3.06
Fe_2O_3	2.13	1.62	1.80	3.29
K_2O	1.72	1.65	1.88	1.88
MgO	0.17	0.14	0.96	0.85
TiO_2	0.28	0.28	0.76	0.76
SO_3	0.01	0.01	0.00	0.00
Loss on ignition	2.18	3.44	1.33	3.78
W_i (kWh/t)	10.55	11.52	11.78	9.95
S_i (min^{-1})	3.397	4.514	4.522	5.267

Fig. 5. A comparison of the S_i, W_i, and especially SiO_2 values from chemical analysis results of four different pumice [a], SEM views of the D-pumice, hypo-crystalline, and vitrophyric texture and more porous, as opposed to the A-pumice [b], and variations in the specific rates of breakage vs. particle size of the pumice samples [c] (from Deniz, 2013)

Deniz (2012) pointed out the relationships between the Bond grindability (G_{bg}) and chemical analysis values of different marl samples and obtained good correlations between the G_{bg} and some chemical analysis values (CaO, SiO_2, and loss on ignition, etc.). In addition, he also investigated the relationships between the G_{bg} and the modulus of the raw material mixture such as cementation index, lime-silica

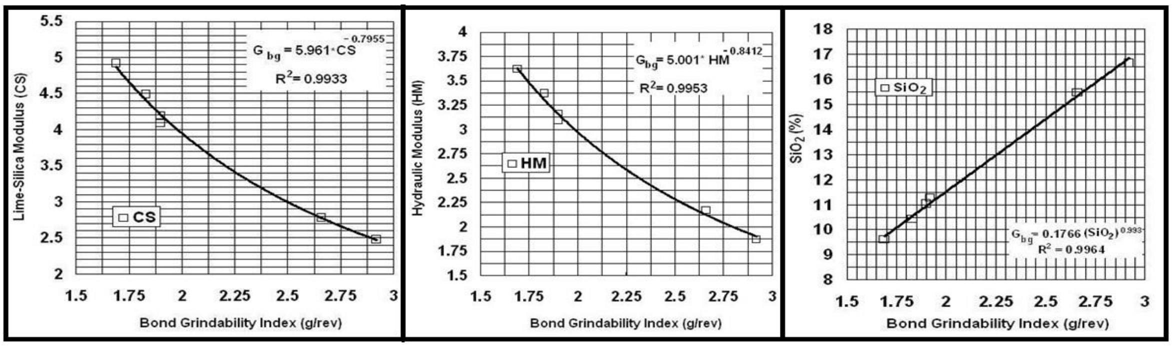


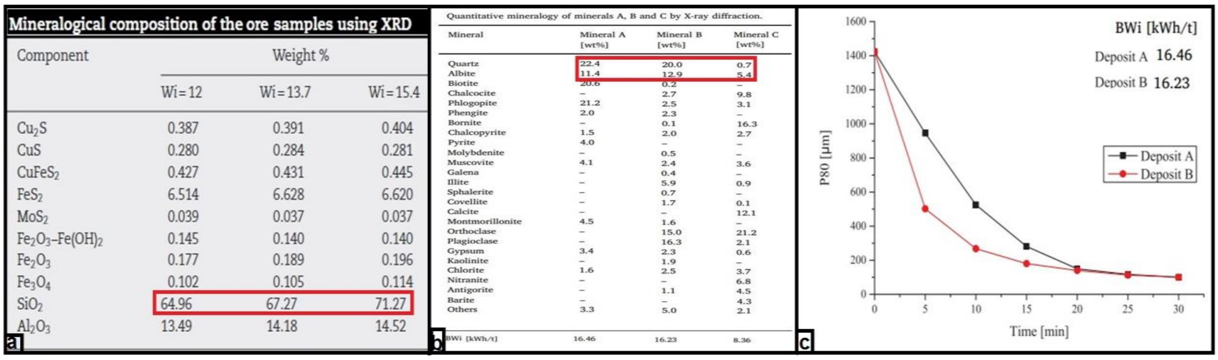
Fig. 6. Views of the relationships between the Bond grindability indexes (G_{bg}) and the Lime-Silica Module, Hydraulic-Module, and SiO_2 values of six different marl samples (from Deniz, 2012)

modulus, hydraulic modulus, lime saturation factor, etc., and the validity of the obtained relationship equations has been confirmed with regression coefficients (r^2) of higher than 0.954, through a simple regression analysis, as seen in some relationships in Fig. 6.

Schmitt (2021) aimed to predict the grindability of the ore from the mineralogical contents and chemical composition information obtained from XRF, XRD, and QEMSCAN tests on samples taken from a porphyry copper deposit with different mica, quartz, and plagioclase contents. He derived linear predictive models with IBM-SPSS by using mineralogical data obtained from XRD and QEMSCAN (mica, quartz, and plagioclase content) analysis in addition to the chemical composition data taken from XRF analysis (Fe, S, CaO, and Al_2O_3). He said that with the help of the relationships defined between the grindability of the ore and the mineralogical and chemical analysis data, a model can be put forward, and based on this information, an intelligent blending strategy can be developed to be integrated into the block model of the mine pit.

Ebadnejad (2016) tested the Bond work indices (W_i, kWh/Mg) for three different copper sulfide ores, and W_i values of copper ores were calculated as 12.0, 13.7, 15.4 kWh/Mg, respectively. According to the results of the analysis made with XRD, it was determined that the main factor affecting the grinding was the excess of quartz minerals, which is the main gangue mineral. Quartz ratios of the samples are 64.96%, 67.27%, and 71.27% SiO_2, respectively, as seen in Fig. 7[a].

Diaz et al. (2018) determined that the main factor affecting grinding was the excess of quartz and albite minerals, according to the W_i values of three different copper sulfide ores, as seen in Fig. 7[b]. In a different study by Diaz et al. (2019), they investigated the effect of geological texture in terms of mineral composition and grain size on the grinding performance of two different copper ores having closer W_i values. Contrary to previous results, they said that two samples with similar W_i exhibited different product size distribution at short grinding times, and they only achieved similar milling products after long grinding times, as seen in Fig. 7[c]. They stated that the reason for this situation was that the different texture properties of the minerals in short grinding times gave different product distribution due to easy breaking in the product.


Mineralogical composition of the ore samples using XRD

Component	Weight %		
	Wi = 12	Wi = 13.7	Wi = 15.4
Cu_2S	0.387	0.391	0.404
CuS	0.280	0.284	0.281
$CuFeS_2$	0.427	0.431	0.445
FeS_2	6.514	6.628	6.620
MoS_2	0.039	0.037	0.037
Fe_2O_3-$Fe(OH)_2$	0.145	0.140	0.140
Fe_2O_3	0.177	0.189	0.196
Fe_3O_4	0.102	0.105	0.114
SiO_2	64.96	67.27	71.27
Al_2O_3	13.49	14.18	14.52

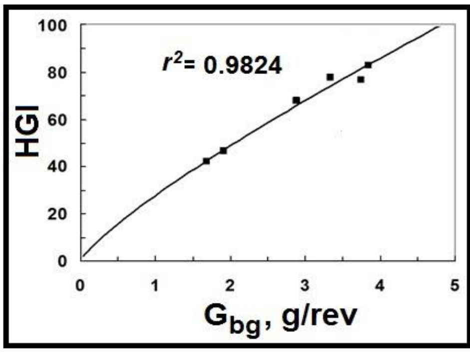
a

Quantitative mineralogy of minerals A, B and C by X-ray diffraction.

Mineral	Mineral A [wt%]	Mineral B [wt%]	Mineral C [wt%]
Quartz	22.4	20.0	0.7
Albite	11.4	12.9	5.4
Biotite	20.6	0.2	–
Chalcocite	–	2.7	9.8
Phlogopite	21.2	2.5	3.1
Phengite	2.0	2.3	–
Bornite	–	0.1	16.3
Chalcopyrite	1.5	2.0	2.7
Pyrite	4.0	–	–
Molybdenite	–	0.5	–
Muscovite	4.1	2.4	3.6
Galena	–	0.4	–
Illite	–	5.9	0.9
Sphalerite	–	0.7	–
Covellite	–	1.7	0.1
Calcite	–	–	12.1
Montmorillonite	4.5	1.6	–
Orthoclase	–	15.0	21.2
Plagioclase	–	16.3	2.1
Gypsum	3.4	2.3	0.6
Kaolinite	–	1.9	–
Chlorite	1.6	2.5	3.7
Nitranite	–	–	6.8
Antigorite	–	1.1	4.5
Barite	–	–	4.3
Others	3.3	5.0	2.1
BWi [kWh/t]	16.46	16.23	8.36

b

Fig. 7. The W_i values and mineralogical compositions of the different copper sulphide ores; according to Ebadnejad (2016) [a], according to Diaz et al. (2018) [b], and Diaz et al. (2019)[c]



Chemical composition of six different limestone samples used in experiments

Oxides (%)	GU	AT	AO	AB	BU	KA
CaO	55.48	54.90	55.77	51.30	55.47	40.50
MgO	0.12	0.26	0.24	2.75	0.29	17.33
Al_2O_3	0.00	0.14	0.01	0.15	0.13	0.12
SiO_2	0.36	0.19	0.42	1.34	0.00	0.00
Fe_2O_3	0.04	0.13	0.03	0.21	0.02	0.05
SO_3	0.03	0.13	0.09	0.19	0.03	0.04
Na_2O	0.00	0.00	0.03	0.00	0.05	0.11
K_2O	0.01	0.04	0.01	0.06	0.00	0.00
Loss on ignition	43.17	43.21	43.39	44.01	42.85	46.03

Fig. 8. The chemical composites and the relationship between the *HGI* and G_{bg} for six different limestones (from Deniz, 2022b)

Deniz (2022b) made both Hardgrove and Bond grindability measurements on six limestones that he determined to contain different amounts of minerals with both XRD and XRF and suggested that different mineral contents significantly changed both grindability values. Also, he demonstrated that there was a good correlation between the *HGI* and G_{bg} grindabilities, as seen in Fig. 8.

4. Effect of comminution on the concentration and liberation properties of ores

Size distribution analysis is performed to assess whether the comminution is accurate and sufficient. From particle size distribution studies, a general estimate of minimum comminution and optimum comminution is obtained for ores or minerals. Therefore, it gives an idea of whether the materials consuming excessive comminution energy have reached the point of over-comminution. In addition, if excessive grinding is done in concentration processes, recovery and concentration rates decrease due to the slime problem.

Mineralogical characterization of ores includes identification of mineral composition and analysis of ore texture. It is very important for mineral processing to also determine the liberation degrees and mineralogical properties of the ores before concentration processes as well as comminution.

Petrographic and mineralogical characterization of ores or minerals includes both mineral composition identification and texture analysis, with tools such as microscopy, XRD, and SEM. Most studies emphasize the importance of the type and amount of minerals present in the ore and relate these to their effects in both comminution and concentration processes.

When deciding on the liberation of ores by grinding, it is important to consider only the liberation of the precious mineral desired to not achieve higher grinding energy. The higher the valuable mineral content, the better the mineral's liberation and the lower the energy required for the desired liberation. It should also be noted that the liberation of the precious mineral may also be affected by texture properties with low mineral content.

Napier-Munn et al. (1996) investigated the grinding relations related to the liberation state of a sphalerite (ZnS) ore and showed that they exhibited different specific fracture rate behavior as a result of grinding the liberated ZnS ore, locked ZnS ore, and gangue, as seen in Fig. 9[a].

Mwanga et al. (2015) stated that a significant difference was observed between the liberation and the grindability in their study of different iron ores. As can be seen in Fig. 9[b], the grindability of two high iron grade samples such as 8F (fine-grained) and 8C (coarse-grained) require quite different grinding energies, but both ores are very similar in terms of liberation. Additionally, Mwanga et al. (2017) conducted a detailed mineralogical study on different iron ores and showed how the particle breakage rate decreases when the particles reach the grain size of the main mineral component on different iron ores. They said that comminution does not increase liberation and that exceeding the grain size limit is just a waste of energy below the grain size. They stated that a significant difference was observed between the mineral fractures of the same iron grade and the gangue minerals due to the texture differences. They also said that the underlying fracture mechanisms influence the liberation of mineral grains and depend on modal mineralogy and mineral texture. As a result of their testing, different mineral textures (i.e. different grain sizes) showed different fracture properties independent of similar magnetite grades (as seen in Fig. 9[c]).

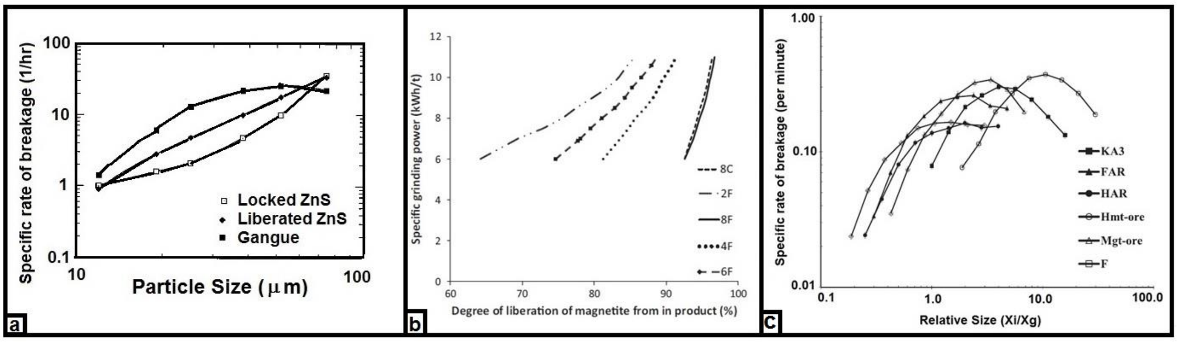


Fig. 9. Variation of the specific rate of breakage vs. particle size of gangue, locked and liberated ZnS [a] (from Napier-Munn et al., 1996), views of the specific power prediction vs. the degree of liberation [b], and the specific rate of breakage vs. relative size for iron ores with different textures [c] (from Mwanga et al., 2015 and 2017)

Wang (2015) conducted a study primarily to provide important information about the mineralogical and textural controls that affect preferential liberation. Mineral distribution and mineral type in the ore with lower tensile strength were observed to play a crucial role in the breakage process.

Yıldırım (2016) presented a relationship between the breaking performance obtained using the single impact load cell test and the degree of alteration (alteration index) obtained using the QXRD and SEM. The importance of single fracture propagation under a single impact was emphasized. Figure 10[b] showed that the first fracture after a single impact on the selected particles did not specifically follow the boundaries between the gangue mineral boundaries. On the other hand, if there is sulphide mineralization such as bornite; fracture tends to follow the sulphide minerals boundary shown in Fig. 10[c]. Thus, sulphide minerals tend to be liberated more quickly when the ore is ground.

Semsari Parapari (2021) stated that the key point for the most efficient process in terms of fracture energy, particle fragmentation, and mineral liberation, is to determine ore texture micro properties. She suggested that the ore texture could influence the fracture mode and liberation and that the intensity of crack formation in a particular mineral indicates natural micro-cracks within the mineral that cause a selective fracture mode (as seen in Fig. 11[a]).

Hatzor and Palchik (1997) reported that fracture initiation stress is inversely related to the grain size of dolomite. Additionally, Eberdhardt et al. (1999) performed the *UCS* to determine the effects of grain size of minerals on the development of stress-induced micro-fractures on three different crystalline rocks. They said that grain size effects had a more significant influence on cracks originating along grain boundaries. Also, they found that even at lower pressing loads, cracks propagating along longer existing planes of weakness coalesced and the strength of the rock decreased with increasing grain size, and showed that following the crack initiation under low stress, fractures occurred in the feldspar grains above the cracks formed along the grain boundaries between quartz and k-feldspar minerals in Fig. 11[b].

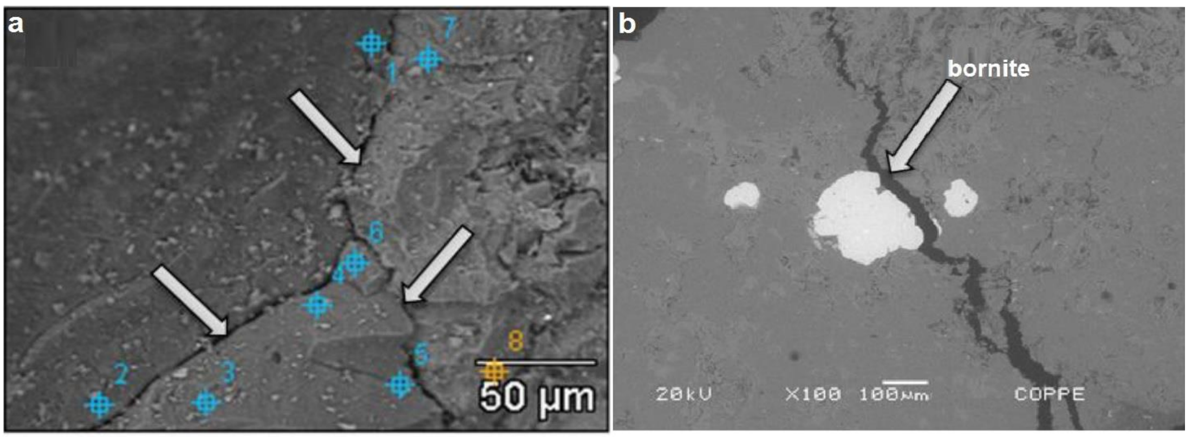


Fig. 10. SEM images of a single fracture that does not follow any mineral boundary [a] (from Yıldırım, 2006), and initial fracture formation (bornite) that may tend to follow mineral boundaries [b] (from Oledele et al., 2021)

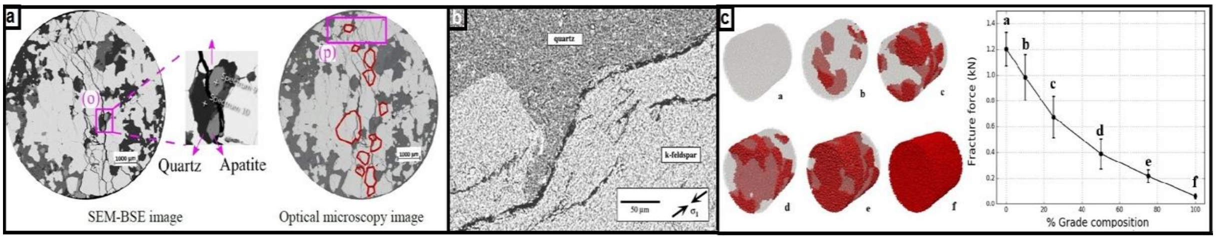


Fig. 11. Crack formation and distribution in texture; Red colour: grain boundaries. (p) and (o) areas: propagated crack between apatite and quartz grains [a] (from Semsari Parapari, 2021), SEM image of stress-induced cracks originating along a quartz-feldspar grain boundary [b] (from Eberdhardt et al., 1999), and variation of fracture force vs. valuable mineral mixture ratio [c] (from Oledele et al. 2021)

Oledele et al. (2021) investigated the influence of the mineralogical composition of numerical rock samples on binary samples consisting of two different mineral phases (the softer one being "valuable mineral" and the other being "gangue") with the bonded particle DEM approach. They evaluated the fracture force of the ore model with six different mineral ratios, one gangue, and the other precious mineral. They showed the typical distributions of valuable minerals at different mineral mixing ratios and the decrease in fracture strength as the valuable mineral mixture ratio increases (Fig. 11[c]).

The ores can be enriched by gravity, magnetic, electrostatic, and flotation methods, but choosing the most economical method is more important than anything else. In addition, the mineralogical, physical, and chemical properties of the ores are very important in the selection of these methods. It has been accepted by some researchers such as Lotter (2010) and Lorenzen & Bernard (2011) that the mineralogy of an ore significantly affects all concentration processes, especially flotation.

The most commonly used concentration methods mentioned above are gravity methods (jig, shaking table spiral, etc.) in terms of both cheapness and simplicity. Taggart, in 1945, theoretically interpreted whether ores could be evaluated in the gravity method with the "Concentration Criterion". For example, if we consider the beneficiation of chromite ore, the specific gravities of serpentine, olivine, and chromite minerals, which are in the ore, are 2.6, 3.3, and 4.6 g/cm^3, respectively. If there apply Taggart's concentration criterion to these minerals, it will be 1.56 for chromite and olivine, 2.25 for chromite and serpentine, and 1.44 for olivine and serpentine, respectively. Chromite mineral is easy to be concentrated due to its high specific gravity compared to serpentine and olivine. However, if serpentine and olivine minerals are all together in the chromite ore, these minerals will act as middlings and adversely affect the concentration recovery and concentrate grade.

In a study on two different chromite ores containing chromite-olivine and chromite-serpentine by Deniz et al. (2001), they determined that the chromite ores due to the different mineralogical properties, the liberation significantly affects the grinding result in terms of grain size. In the mineralogical investigations of both ores given in Fig. 12, in the chromite-olivine ore, the intercrystalline porosity of the subhedral chromite crystals is filled with un-hedral and frequently fractured olivine crystals, and it has been observed that the chromite crystals generally fracture due to tectonic effects to obtain the cataclastic texture (Fig. 12[a]). In the chromite-serpentine ore, wall-rock is completely serpentine ultra-basic rock and wall-rock consists dominantly of serpentinized dunite (Fig. 12[b]). The results of the

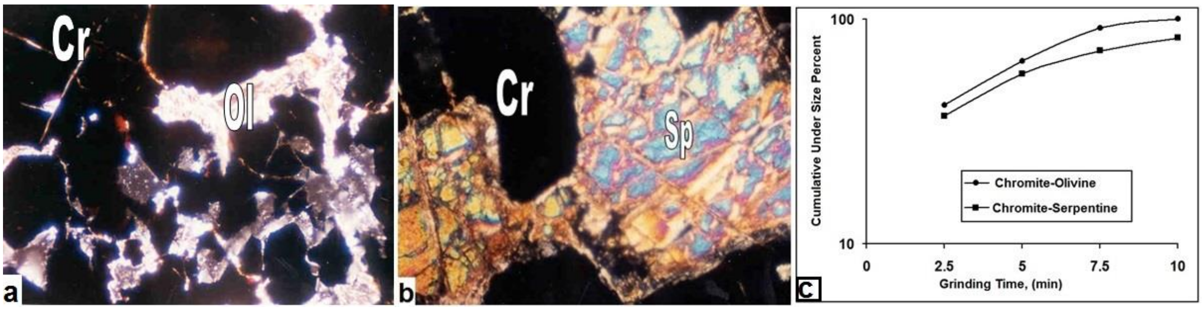


Fig. 12. View of chromite-olivine ore [a], chromite-serpentine ore [b], and the grinding behavior difference of chromite ore according to different gangue minerals (olivine or serpentine) [c] (from Deniz et al., 2001)

grinding tests of two different chromite ores were given in Fig. 9[c]. The grinding times of chromite-olivine and chromite-serpentine ores with the same liberation grain size were found to be 6.5 and 9.5 minutes, respectively. It was determined that the reason for the difference in two different grinding results was due to different textures from each other in the mineralogical studies of two different chromite ores.

Mineral liberation is one of the key factors that determine flotation performance. The valuable minerals entering a flotation plant are not allowed to be fully liberated from gangue minerals due to industrial comminution costs and often some remain bound with gangue minerals. Therefore, the economics of comminution-flotation plants are strongly linked to the mineralogy of bound grains and ores. However, in recent years, with the emergence of SEM, QEMSCAN, and other image analysis methods, which can more easily determine the liberalization for the optimization of flotation circuits, optimization of flotation circuits, can be made continuously.

Flotation is an important method used in the concentration of fine and very fine particles (-0.3 mm) based on the surface property differences of minerals. Particle surface chemistry and grinding conditions are some of the considerations to control the success of the flotation process. Particle size distribution and mineral liberation are the most important determining factors for a flotation, controlled by the grinding conditions such as dry/wet environment, types of comminution mechanism, and the rate of ball and liner corrosion. These differences in the comminution process can both affect the flotation recovery and also change the properties of the grinding products. However, to date, a few works have been done to compare the effects of comminution on flotation.

The effect of liberation upon flotation performance is well established. Evaluation of performance in flotation plants is usually evaluated by their contents obtained from chemical analysis of feed and products (concentrate and waste). However, the results of chemical analysis alone are not sufficient to evaluate and optimize flotation, as it cannot provide any data about the texture and liberation states of minerals. The performance of the flotation plant can easily be decreased because of changes in the mineralogy and texture of the ore in the long run. Therefore, to keep the flotation performance stabilized and control the effects of probable changes which may happen during production, petrographical and mineralogical studies of ores are required (Sutherland, 1998).

Tungpalan et al. (2015) studied of flotation behaviour of four different copper porphyry ores by examining their mineralogical and textural features. They said that the influence of grain size distribution and mineral association of copper sulphides to copper recovery.

In the grinding study of Shalchian et al. (2017) on molybdenum ore, they showed that molybdenite exhibited different grinding behavior than other sulfide minerals due to its anisotropic properties, and SEM–TEM images (Fig. 13) showed how MoS_2 was broken in layers. In Fig. 13, they said that since S–Mo–S layers in hexagonal molybdenite are covalently bonded by Van der Waals forces, the surface-to-edge ratio decreases as the size of molybdenite particles decreases, which causes an increase in the hydrophilic properties of molybdenite. Therefore, the floatability of molybdenite will reduce.

Liu et al. (2018) showed that the grinding medium on the flotation of two different copper sulphide ores had some effects on the particle size distributions and the copper grade of the feed, the electrochemical parameters of the pulp, and hence the flotation performance. They examined the

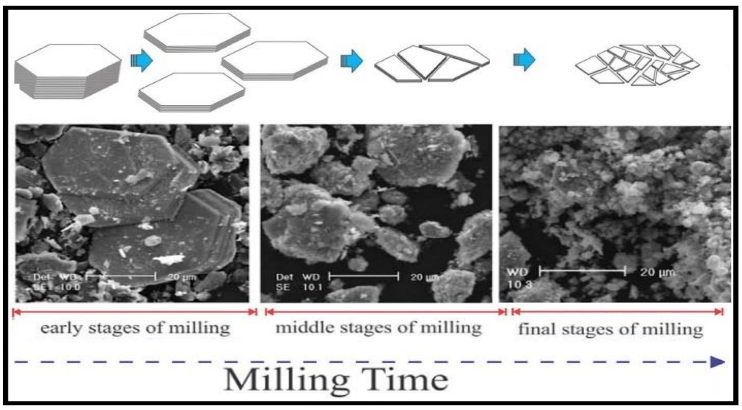


Fig. 13. SEM-TEM image of molybdenite ore with respect to grinding time (from Shalchian et al., 2017)

behavior of the suspension Eh depending on the grinding time of two different copper ores (LJ and DX copper ores) with and without lime addition and it was quite different as can be seen in Fig. 14[a]. In particular, the corresponding changes in Eh values were interesting when without lime. Additionally, they said that the extent of this effect depends on the ore, which can be explained by considering the mineralogy of the ores, as seen in Fig. 14[b].

Bradshaw (2014) has a comparison in terms of both liberation and copper flotation between a limestone skarn copper ore (LSN) and a monzonite-copper ore (MZME3). The mineralogical studies showed that the copper minerals were found to be very finer in the LSN ore than MZME3 ore, leaving the potential for a greater quantity of un-liberated Cu-bearing grains in the coarse size fractions. Theoretical grade vs. recovery curves produced by Bradshaw (2014) from QEMSCAN mineralogical data on copper ore with two different mineralogical properties, MZME3 and LSN, highlight lower liberation of copper minerals in coarse particles of LSN compared to MZME3 ore, as shown in Figs. 15[a] and 15[b]. These results are supported by the lower copper recovery from laboratory flotation test results in coarse size fractions for the LSN ore shown in Fig. 15[c].

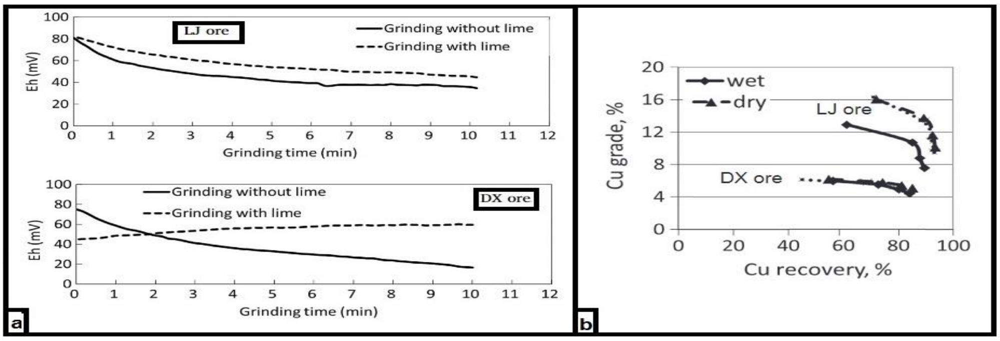


Fig. 4. The Eh changes vs. grinding [a] and the curves of Cu-grade vs. recovery time of two different ores [b] (from Liu et al., 2018)

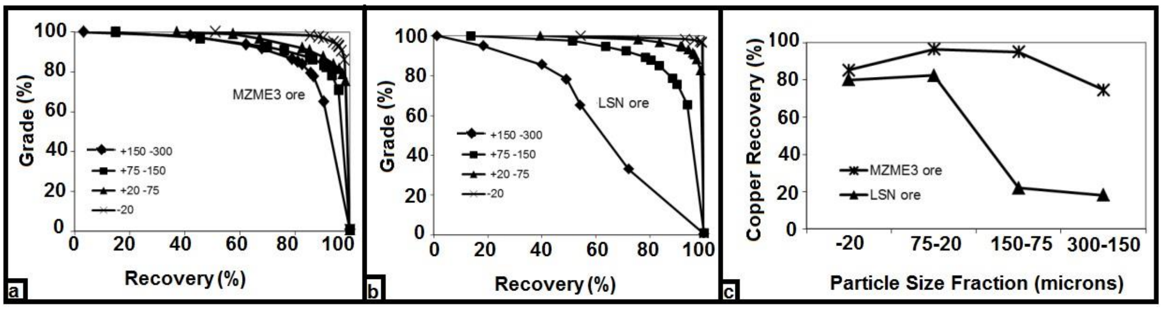


Fig. 15. Variation of Cu grade versus recovery in flotation for the two different copper ores [a and b] and variation of Cu flotation recovery vs. particle size fractions [c] (from Bradshaw, 2014)

Welsby (2009) said that the flotation kinetic constant as a function of particle sizes and the liberation degree of minerals follows first-order dynamics, as seen in Fig. 16[a]. Thivierge et al. (2019), just like Welsby (2009), fitted the flotation kinetic constants versus particle size to their laboratory data as shown in Fig. 16[b]. Rincon et al. (2019) performed bulk sulphide flotation where have shown similar flotation behaviour achieving a recovery above 90% on 10 different copper ores and obtaining very different performance results. They summarized the results where each point represents copper concentrates taken at different flotation times, as seen in Fig. 16[c]. They said that the difference in flotation performance could be due to mineralogical variability between samples.

5. Conclusions

Determining the effects on the comminution behavior of chemical, petrographic, and mineralogical properties of ores or minerals is very important to obtain information about the comminution behavior of the ores and even the concentration efficiency. Evaluating the effects of these properties of ores on

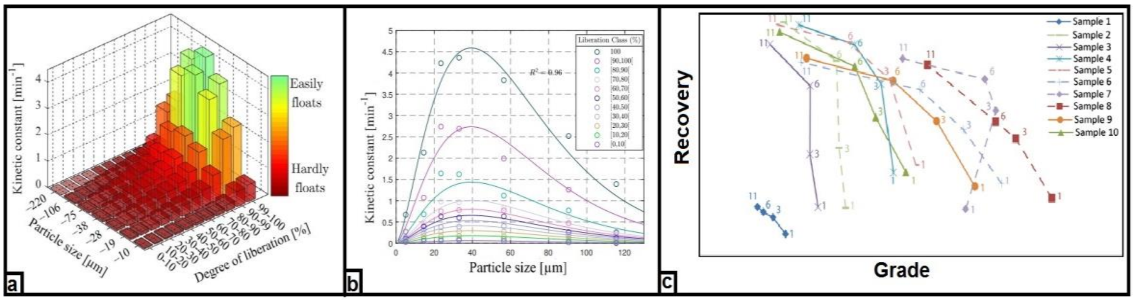


Fig. 16. Variation of flotation kinetic constant as a function of particle size and liberation degree (Welsby, 2009 [a]; Thivierge et al., 2019[b]), Cu grade vs. recovery in flotation for different copper ores [c] (Rincon et al., 2019)

their comminution behavior, both immediate and later, is crucial in many mineral processing plants. However, since ore texture laboratory tests are difficult, not ubiquitous, and expensive, and test analysis requires expertise, investigations between comminution properties and chemical and textural properties of mineral or ores based on experimental test data are not carried out much.

On the other hand, the evidence for obtaining precise regressions between the comminution properties of ores and their chemical, petrographic and mineralogical properties is not sufficient. Because most of the regression equations between the comminution behavior of ores and their chemical, petrographical, and mineralogical properties are based on either one or two minerals in the ore. In fact, the effects of ores containing more than two minerals, and especially low-content minerals, on the comminution have not been studied in detail yet.

Various models should be developed to determine the effects of chemical, petrographical, and mineralogical properties of ores on their comminution efficiency. The comminution is also related to the liberation and concentration of ores, especially the flotation method in the mineral processing plants. Therefore, in the next years, researchers should focus on the relationships between the liberation and concentration efficiency and the chemical, petrographical, and mineralogical properties of the ores. If all these factors are taken into account, it would be simple and useful to apply these techniques to all mineral processing plants for the prediction of comminution behavior.

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