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Chapter

The Effects of Mill Conditions on Breakage Parameters of Quartz Sand in the District of Şile on the Black Sea Coast of İstanbul

Serhan Haner

Abstract

Casting, glass, ceramic, construction, plastic, dyeing, and abrasive industries are the main consumption areas of quartz sand, which are formed as a result of the weathering of igneous metamorphic rocks. In such industries, it is very important to select the correct ball size in order to grind the raw material to the desired particle size in optimum time. In this study, the changes in the specific rate of breakage of the quartz sand sample were investigated by using alloy steel balls of five different sizes. For this purpose, three different mono-size samples were prepared according to $\sqrt[4]{2}$ series in the range of 0.090–0.053 mm. The quartz sand prepared in these three intervals was ground with 6.35, 7.94, 9.52, 12.70, and 19.05 mm alloy steel balls for different durations. The specific rate of breakage values was obtained from the particle size distributions acquired after various grinding periods. As a result of grinding tests, an increase in the rate of breakage is observed due to the increase in ball diameter.

Keywords: quartz sand, breakage, ball size, comminution, Şile, İstanbul

1. Introduction

Turkey has 2.5% of the global industrial mineral reserves, 73% of the global boron mineral reserves, 20% of the global bentonite reserves, and more than half of the global perlite reserves. The mines extracted from these sources are used as raw materials in the industry, with the excess being exported. Around 791 million tons of industrial minerals are produced worldwide, and Turkey accounts for 42.3 million tons of this global production. Turkey ranks 3rd in the world with a share of 5.3% in industrial mineral production. When we consider this production rate in terms of value, it ranks 8th with a 4 percent share. Based on the figures for 2016, the mines extracted most in Turkey's industrial raw material production were calcite, feldspar, gypsum, quartz sand, pumice, and boron. These production data were drawn up based on the production amount figures declared by licensed mine sites to the Turkey General Directorate of Mining and Petroleum Affairs.

Quartz sand deposits are very common in Turkey. There are quartz sand deposits in İstanbul-Şile and Çatalca, Zonguldak-Kilimli, Bartın, Tekirdağ-Safaalan and Sinop-Sarıkum. In Turkey, there are 1.884.208.585 tons of (visible+probable) quartz sand reserves containing over 90% SiO_2. A total of 54.820.154 tons of quartz sand were produced in Turkey between the years 2011 and 2016.

Quartz sand is formed as a result of the decomposition of quartz-rich magmatic metamorphic rocks. Quartz sand is divided into two types based on its formation. Magma-origin rocks have decomposed and weathered where they formed by physical forces such as the atmosphere and faults. These deposits have higher SiO2 content. Some other deposits piled up in one area during being moved and formed placer beds. During transportation, heavy minerals also collapsed and turned into deposits when moving with the silica. Quartz sand consists of silica particle of 1/16 and 2 mm size. Its pure one is white in color. On the other hand, depending on the amount of iron minerals (limonite, pyrite, magnetite, hematite, etc.) in it, it can be brown, red, or pink in color. It contains a high amount of silica. Although it can be found pure in nature, it may contain small amounts of clay, feldspar, iron oxides, or carbonates. The beneficiation processes such as gravity, frotation, and leaching are applied in order to bring the requested chemical, physical, or thermal properties depending on the intended use. According to their intended use, quartz sands are generally named core sand, glass sand, golf course sand, hydraulic fracturing sand and blasting sand. In determining the usage area of quartz sand, it is important to know the maximum chemical impurity and minimum SiO_2 levels, and the features such as particle size distribution and grain shape. There must be at least 95% SiO_2 in quartz sand to be used in the production of casting mold, silica bricks, silicone, ferrosilicon, and building sand, and there are certain limit levels for Al_2O_3 and Fe_2O_3 content. Quartz sand is in a general sense used in the glass and casting industry. Apart from these areas of application, it is also used in industries such as construction, aerated concrete, ceramic, iron-steel, dyeing, plastic, and abrasive, which is used for removing rusted surfaces, corroded surfaces, old paint, as well as for shaping marble and glass. The open-pit mining method is applied as the production method from the pit. For quartz sand production to be economical, the ratio of the thickness of the cover layer to the thickness of the quartz sand layer should not exceed the 4 m^3/ton level [1–4].

In this study, quartz sand in the district of Şile on the Black Sea Coast of İstanbul, Turkey, which is used in the production of traditional ceramic materials, is preferred. Over 4 million tons of quartz sand are produced annually from the Şile Basin and utilized in many fields in Turkey. Şile region quartz sand reserves are estimated to be over 100 million tons. In the traditional ceramics industry, quartz sand containing 90% > SiO_2 and $Fe_2O_3 < 0.5\%$ with a particle size of approximately $-1 + 0.075$ mm is preferred. The quartz sands of the Şile region generally have the characteristics to meet these expected oxide properties. Mining companies sell these quartz sands only after they have been washed and classified. Non-plastic raw materials such as feldspar and quartz sand supplied by traditional ceramic factories are also applied to the grinding process. Generally, an alumina ball is used as the grinding medium in the grinding process to give ceramic materials the desired physical, chemical, thermal and mechanical properties. Ball mills are preferred for intermediate grinding (P80; 0.040 to 0.40 mm) in plants producing traditional ceramic products such as tile, sanitaryware, tableware, and. The non-plastic composition is ground to a particle size finer than 0.075 mm with the grinding process. After the grinding process, the Fe_2O_3 content in the ceramic sludge is removed with magnetic holders.

Upon examination of the quartz sand of the Şile region, which was supplied for use in the studies, with a loop, dark-colored ferrous minerals with a grain size of approximately 0.010–0.040 mm were discovered. These minerals, which do not pose a significant problem in the traditional ceramic industry, can be considered as an essential impurity in areas such as glass and casting mold production. If it is necessary to obtain quartz sands with higher SiO_2 and lower Fe_2O_3 content, such as glass and casting mold production, enrichment processes must be applied. In such cases, quartz sands are enriched by gravity method, flotation, or extraction according to their intended use, and the impurities it contains are removed. In the gravity method, first of all, the clay minerals that form slime must be cleaned. Then, minerals with magnetic properties such as hematite, magnetite, or ilmenite must be removed with magnetic separators of 1000–15,000 gauss intensity. Wet magnetic separators are preferred for cleaning magnetic minerals smaller than 0.075 mm. Enrichment by gravity becomes increasingly challenging as the grain size decreases. As in the quartz sand of the Şile region used in this study, some impurities can be liberated in grain sizes below 0.075 mm. In such cases, the quartz sand must first be ground into the liberation size. Afterward, enrichment by flotation is required [3, 5]. Since the grinding process is under a specific particle size, most of the energy used is converted into heat energy. While specific energies of ball mills increase exponentially in these fine particle sizes, the grinding efficiency decreases economically [6–10].

Quartz sand acts as a grinding medium on other non-plastic raw materials that form the ball mill phase in ceramic materials production. Raw materials such as feldspar in the mill show fracture along smooth surfaces because they have cleavage. However, since quartz sand is no cleavage, it does not show the smooth fracture. Fracture occurring along irregularly developed cracks in quartz sand takes place conchoidally (mussel shell) [11]. As a result, when compared to other raw materials in the mill, quartz sand grinding and the energy consumed during this operation are significantly high. It also causes some wear on grinding media such as quartz sand, alumina ball, and flint pebbles. In this study, alloy steel balls were favored as a grinding medium in grinding units above alumina balls and flint pebbles, which are preferred by ceramic producers. Alloy steel balls have approximately twice the specific gravity of alumina balls. The grinding medium's weight applied to the unit volume during the grinding process and the size of the grinding medium are critical elements determining the mills' capacity and efficiency. There are some studies in the literature on the selection of the grinding medium size in the ball mill [6, 12–17]. In addition, there are studies of breakage rate parameters of some raw materials [18–20].

In this study, the effect of different sizes of alloy steel balls on specific rates of breakage (S_i) was investigated. The quartz sand used in grinding works was supplied by a private mining company, which is located in the district of Şile, Istanbul. The variation of the specific rate of breakage of quartz sand was investigated using 6.35, 7.94, 9.52, 12.70, and 19.05 mm alloy steel balls. For the grinding tests carried out in dry conditions, the powder (f_c = 0.120) and ball loads (J = 0.35) are taken as fixed. For this purpose, the kinetic model, the basis of which was developed by Austin et al. (1984), was applied. In this model, mathematical expressions are defining the breakage distribution and breakage rate of raw material [21]. Studies with kinetic model-based grinding and the values obtained in the laboratory are suitable for simulation in an industrial environment [22].

2. Materials and methods

Quartz sand used in laboratory-scale grinding experiments was obtained from a private mining company located in Şile, on the Black Sea coast of İstanbul. Chemical analysis values of quartz sand are given in **Table 1**.

In this study, specific rate of breakage values of Şile region quartz sand in three different mono-size intervals were determined. For this purpose, Şile region quartz sand was prepared in mono-size intervals of $-0.090 + 0.075$, $-0.075 + 0.063$, $-0.063 + 0.053$ mm according to the $\sqrt[4]{2}$ sieve series. In order to determine the specific rate of breakage values of quartz sand, a 150x150 mm (diameter x length) stainless steel ball mill was used as the grinding medium. The diameters of the grinding balls in this grinding medium were chosen as 6.35, 7.94, 9.52, 12.70, and 19.05 mm. In order to determine the specific rate of breakage values of quartz sand in three mono-size intervals, it was ground in batches at certain time periods (1, 2, 4, 8, 16, 32, and 64 minutes). After each grinding period, all the powder in the mill was discharged, and representative samples were taken. A laser diffraction device was used to measure the particle sizes of the representative samples belonging to the grinding periods. Based on each time period of grinding, semi-logarithmic graphs of the material fractions staying in the high points of the particles' size limits were drawn in contact with the grinding periods. The first-order zone breakage is represented by the zone in which this graph decreases linearly. The slope of the line in the first-order breakage zone gives us the specific rate of breakage of the material in that particle size range. The formula for the specific rate of breakage (S_i) is given in Eq. 1.

$$S_i = a(\mathrm{x_i}/1\ \mathrm{mm}\ )^{\alpha} Q_i \tag{1}$$

The symbol "a" given in Eq. 1 is the model parameter. This parameter depends on the mill conditions. "α" value is a positive number, normally in the range 0.5 to 1.5, which is characteristic of the material properties. "x_i" symbolizes the upper dimension (mm) in the fraction i. Q_i is the correction factor and is taken as 1 for smaller sizes. The experimentally established values of Q_i can be seen in Eq. 2 [21].

$$Q_i = \frac{1}{1 + (x_i/\mu)^{\Lambda}} \qquad \Lambda \geq 0 \tag{2}$$

SiO_2	91.16
Al_2O_3	5.18
Na_2O	0.62
K_2O	0.37
CaO	0.05
Fe_2O_3	0.34
TiO_2	0.43
SO_3	0.03
Loss on ignition	1.82

Table 1.
Chemical composition of quartz sand, mass-%.

Eq. 2 refers to the fact that "μ is the particle size at which the correction factor 1/2 and Λ a positive number which is an index of how rapidly the rates of breakage fall as size increases (the higher the value of Λ, the more rapidly the values decrease)" [21].

In laboratory grinding studies, the rotational speed of the ball mill was chosen to be 70% of the critical speed value of the ball mill. The critical speed of the ball mill was calculated using Eq. 3. Amounts of ball and material to be fed to the mill with Eqs. 4–6 respectively and the mill's interstitial filling rates were found.

$$\text{Critical speed } (N_c) = \frac{42.3}{\sqrt{(\mathrm{D} - \mathrm{d})}} \tag{3}$$

In Eq. 2, D represents the internal mill diameter (m) and d represents the maximum ball diameter (m) [21].

$$J = \frac{\text{Mass of balls/Ball density}}{\text{Mill volume}} * \left(\frac{1}{0.6}\right) \tag{4}$$

$$f_c = \frac{\text{Mass of powder/Powder density}}{\text{Mill volume}} * \left(\frac{1}{0.6}\right) \tag{5}$$

$$U = \frac{f_c}{0.4 * J} \tag{6}$$

The properties of the ball mill, experimental conditions, alloy steel balls, and quartz sand used in the laboratory grinding process are given in **Table 2**.

Shoji et al. (1982) found a simple relationship between powder filling and ball load in the mill [23]. It is seen in Eq. 5. In Eq. 6, the net mill power (m_p) as a function of ball load was fitted by the empirical function. Eq. 7, which is the combination of Eqs. 5 and 6, was used to calculate the specific grinding energy as a function of ball filling. Combining Eqs. 5 and 6 gives the result shown in **Figure 1** [21].

Mill	Diameter, D mm	150
	Length, mm	150
	Volume, mm^3	2650x10^3
Mill speed	Critical (N_c), rpm	111–117
	Operational (Ø_c = 70%), rpm	78–82
Ball	Quality	Alloyed steel
	Specific gravity, g/cm^3	8.09
	Diameter, d mm	6.35, 7.94, 9.52, 12.70, 19.05
	Fractional ball filling, J	0.35
Material	Specific gravity, g/cm^3	2.65
	Fractional powder filling, f_c	0.12
	Powder-ball loading ratio, U	0.86

Table 2.
Ball mill characteristics and test conditions for grinding of quartz sand.

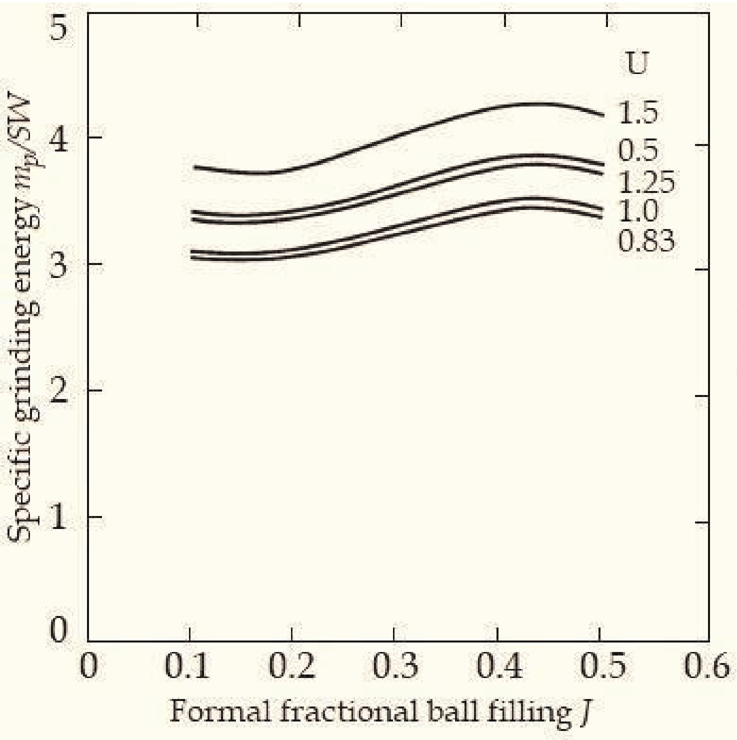

Figure 1.
Relative specific grinding energy as a function of ball filling: dry grinding in a laboratory mill [18].

$$S(f_c, J) \propto a \propto \frac{1}{1+6.6J^{2.3}} \exp[-cU], 0.5 \le U \le 1.5, 0.2 \le J \le 0.6 \tag{7}$$

where c is 1.32 and 1.2 for wet and dry grinding respectively.

$$m_p \propto \frac{1-0.937J}{1+5.95J^5}, \quad 0.2 \le J \le 0.6 \tag{8}$$

$$\text{Specific grinding energy} \propto \left\{\frac{1-0.9375J}{1+5.95J^5}\right\} / \left\{\frac{Ue^{-1.2U}}{1+6.6J^{2.3}}\right\} \tag{9}$$

Austin et al. (1984) express the connection between specific grinding energy and ball load as follows: "Although the capacity of a laboratory mill is a maximum at 40 to 45% ball load, the relative specific grinding energy m_p/SW is a minimum at about 15 to 20% ball load. In practice, ball loads less than 25% are not normally used because low ball loads can give excessive liner wear. In addition, mill capacity is clearly lower for lower ball loads [21]." Dependent upon Eq. 7 and **Figure 1**, the values of specific grinding energy changes based on the ball loads J and powder-ball loading ratio U. As a result, in this study the specific grinding energy values are obtained from Eq. 7 for 0.35 ball filling ratio was calculated as 3.38.

3. Results and discussion

The quartz sand in the three different mono-size intervals were grinding linearly with increasing grinding times. At the end of each milling period, the fractions of material remaining in the top particle size range were plotted against milling times. The graphs of the first-order breakage lines obtained for five different ball sizes are given in **Figures 2–4**. The region where the graph decreases linearly represents the first-order breakage region. The slope of the line in the first-order breakage region gives the specific rate of breakage based on the particle size range of the quartz sand.

After determining the specific rate of breakage for the three mono-size intervals fractions exhibiting first-order breakage kinetics behavior, S_i values were plotted against particle size fraction. The rate of breakage parameters of these lines was determined as a_T and α. The results are given in **Figure 5**.

a_T and α values, which are parameters of specific rates of breakage, were obtained by non-linear regression (from Eq. (1) and **Figure 5**), and are 0.15, 0.85 for 6.35 mm and 0.14, 0.78 for 7.94 mm and 0.14, 0.76 for 9.52 mm and 0.24, 0.95 for 12.70 mm and 0.26, 0.96 for 19.05 mm, respectively. In **Figure 5**, specific breakage rates also decreased based on the decrease in alloy steel ball size in general. Moreover, when the graphics in **Figure 5** are evaluated based on the particle size, the breakage rates

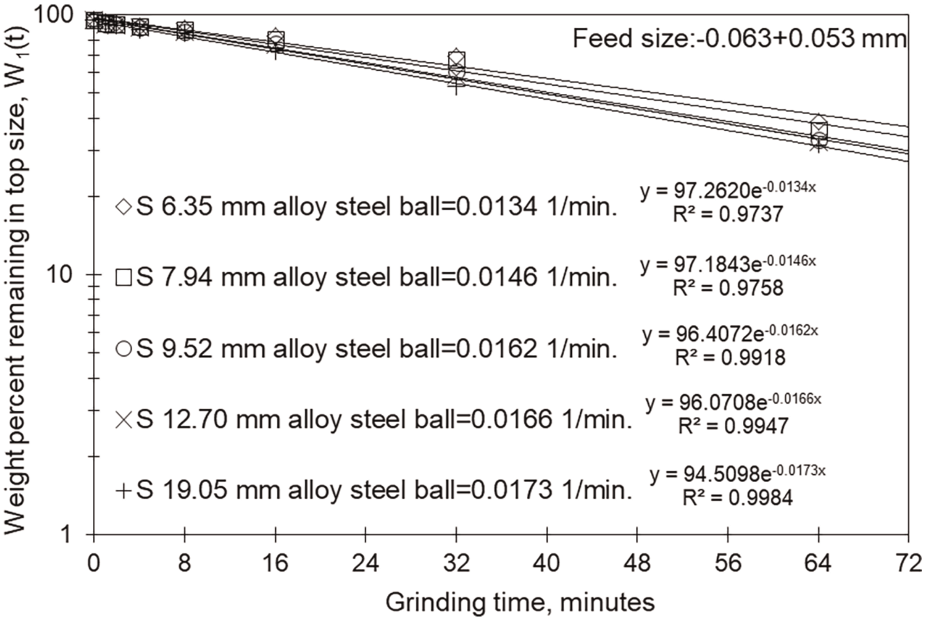

Figure 2.
First-order plots for alloy steel balls with different diameters of quartz sand as well as −0.063 + 0.053.

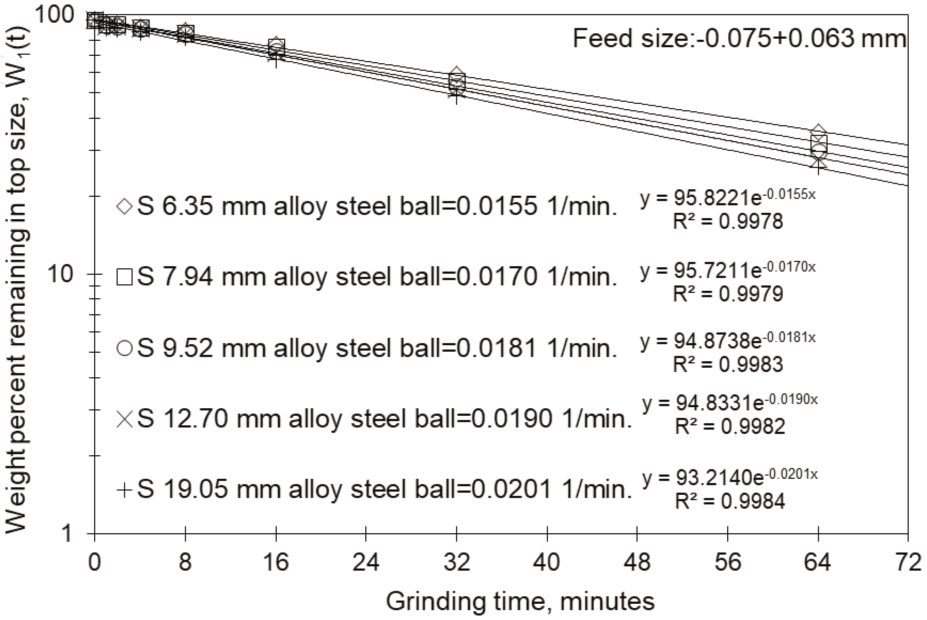

Figure 3.
First-order plots for alloy steel balls with different diameters of quartz sand as well as −0.075 + 0.063.

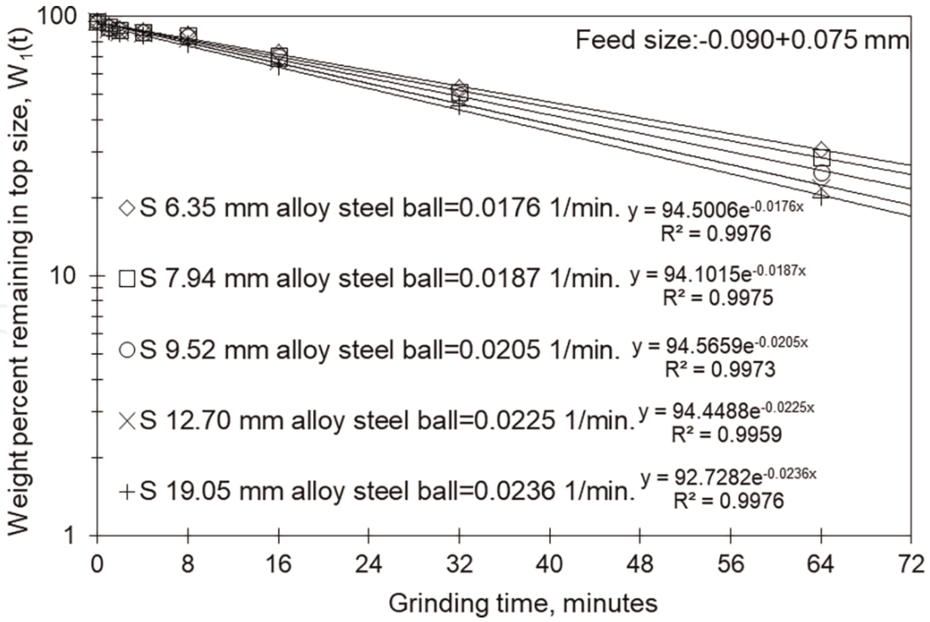

Figure 4.
First-order plots for alloy steel balls with different diameters of quartz sand as well as −0.090 + 0.075.

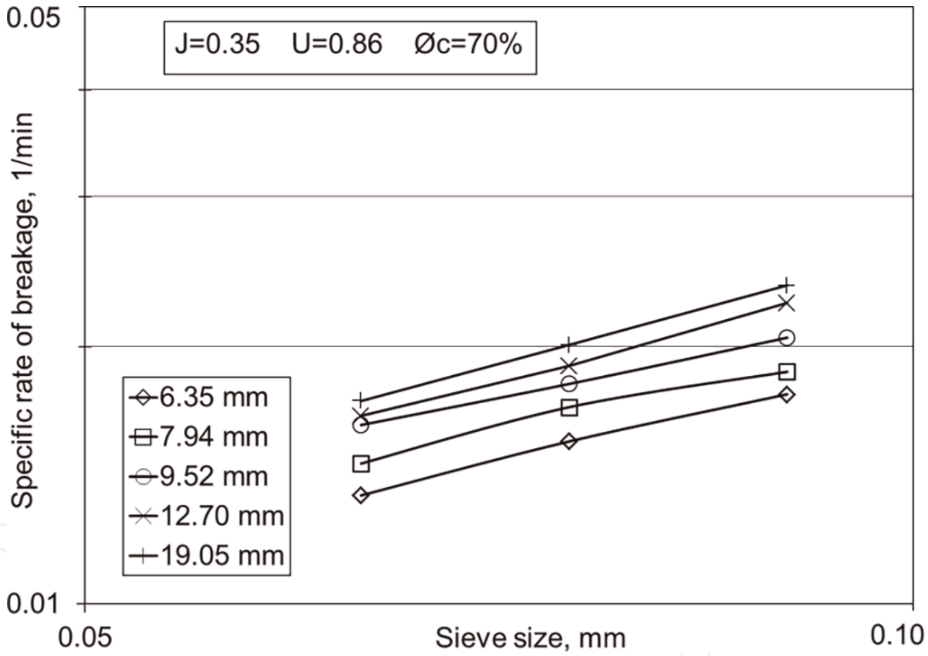

Figure 5.
Variation of the specific rate of breakage as a function of the maximum feed size for quartz sand ground with different alloy steel balls.

decrease as the particle size intervals decrease. The presence of a maximum is quite logical because large lumps obviously will be too strong to be broken in the mill. Austin et al. (1984) explain that "[t]he theory of fracture implies that smaller particles are relatively stronger because larger Griffith flaws exist in larger particles and they are broken out as size is reduced. The fact that the specific rates of breakage are a simple power function of size has not been adequately explained on a theoretical basis, but it has been amply demonstrated by many experiments [21]."

In ball mills, large balls are known to be responsible for the breakage of coarse particles, and small balls are supposed to grind the fine ones. Austin et al. (1984)

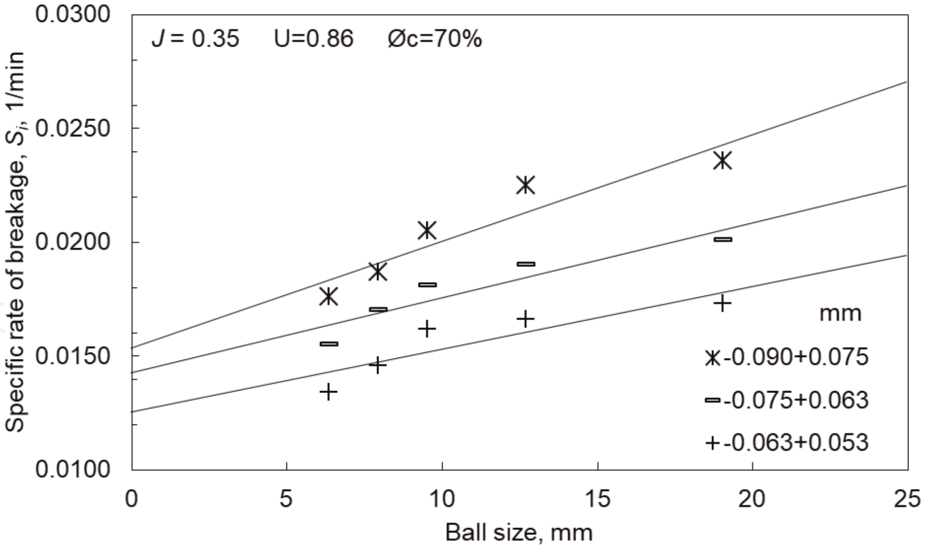

Figure 6.
Variation of ball diameter with first order breakage constant.

stated the effect of ball diameter on breakage rate as "considering a representative unit volume of the mill, the rate of ball-on-ball contacts per unit time will increase as ball diameter decreases since the number of balls in the mill increases as $1/d^3$. Thus, the rates of breakage of smaller sizes are higher for smaller ball diameters [21]." However, balls in the range of 20 mm–50 mm were used for grinding the raw material with a particle size of 30x40 mesh here. The grinding conditions in this study are not the same. According to $\sqrt[4]{2}$ sieve series, 3 mono-sized fractions in the range of $-0.090 + 0.053$ were used. The grinding process was performed with alloy steel balls in the range of 6.35–19.05 mm. It is understood from the results that the grinding was difficult due to working in too small particle size ranges. In **Figure 6**, it can be said that the grinding energy that large-sized balls transferred on the quartz sand particles is high and therefore, high specific rates of breakage values were obtained in the grinding works carried out with large-sized balls. It can be seen that the grinding process is carried out faster by using large-sized balls compared to small-sized balls. This study was shown that $d = 19.05$ mm was the optimum balls size for the maximum breakage rates.

4. Conclusions

Quartz and quartz sand consumption in the traditional ceramics industry in Turkey is approximately 600.000 tons per year. The quartz sand, which has the features that can meet the needs of Turkey's ceramics industry in terms of cost and chemical content, is produced in Şile, İstanbul. Glass quality quartz sand beds have decreased around İstanbul. The quartz sand beds in Turkey are suitable for casting and ceramics industries except for glass. Quartz sands separated by washing in some clay deposits are being evaluated. In addition, as a result of the evaluation of side products in the ore dressing facilities in some raw material quarries that are not economically operable, the operation of these quarries will be possible. It is essential to keep the energy consumed in downscaling processes at an optimum level in order to ensure the economy in raw material production. When the literature is examined, it is seen that many raw materials used for different purposes do not have breakage values under different milling conditions. Breakage values of raw materials belonging to any region differentiate according to their properties such as mineral rates in the raw material, its structural features, chemical impurities, and physical fractures. Therefore, in order for the ore dressing facilities to keep the energy consumed in grinding processes at an optimum level, the grinding kinetics of the raw material must be taken into account.

Accordingly, in this study, the impact of ball size on the grinding characteristic of quartz sand in the district of Şile on the Black Sea Coast of İstanbul in the laboratory ball mill was examined. These quartz sands are rather used in the production of traditional ceramics materials. However, if it is enriched by flotation, it can also be used in different industries. Grinding and classification processes must definitely be applied in order for the quartz sands to be used in any other area of the industry. That is, it is desired that the particle size is in a certain range. The grinding process in the traditional ceramic industry is carried out with ball mills and generally uses alumina balls. A large part of the energy consumed in grinding processes carried out in rod and ball mills turns into sound and heat energy. The grinding efficiency decreases due to this situation. It is very important to choose balls with the appropriate size to reduce the inefficiency of grinding.

In this study, it was found that very small ball sizes could not play an effective role in grinding quartz sand and that their impact and attrition effect on the particles was low. The energy transferred by the steel balls to the quartz sand particles during grinding increased with the increase in ball size. In this study carried out with different ball sizes, it was found that the most effective breakage was achieved with d = 19.05 mm alloy steel ball.

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