Breakage parameters of some minerals and coals ground in a laboratory size ceramic mill

A Ozkan*, M Yekeler & S Aydogan

*Selcuk University, Department of Mining Engineering, 42031, Konya, Turkey
& Cumhuriyet University, Department of Mining Engineering, 58140, Sivas, Turkey

Received 26 December 2002; accepted 1 May 2003

The kinetics of batch dry and wet grindings of calcite, barite, quartz, lignite and anthracite from feeds of sieve size -425+300 μm has been determined using a laboratory scale ceramic ball mill. The $S_i$ values obtained were the highest (0.294 min$^{-1}$) for anthracite and the lowest (0.071 min$^{-1}$) for quartz when ground dry. However, the wet grinding of these materials gave higher $S_i$ values by a factor of 1.28 for calcite, 1.15 for barite, 1.25 for quartz, 1.11 for lignite and 1.07 for anthracite comparing to the dry $S_i$ values. The $B_{ij}$ values also changed for all the materials ground as dry and wet. The simulations of the product size distributions for both first-order and non-first order breakage of the materials ground were in good agreement with the experimental size distributions. There is a relationship between the $S_i$ values and the $γ$ value of $B_{ij}$ parameter; i.e., $S_i$ values increase when $γ$ values decrease, indicating that faster breakage rates of top sizes produce more fines in the finer size distribution region (-150 μm).

The grinding of minerals and other solids is widely used as a processing step in the production of ceramics, glass, cement, pigments and refining of ores. Thus, size reduction by grinding is an important industrial operation involved in many aspects of the mineral, metallurgical, power and chemical industries. Increased rates and efficiencies of milling have been sought through the optimization of milling by providing favourable physical and operational conditions for the mills used. The design and scale-up of ball mills are important issues in size reduction processes. Therefore, various models are used for predicting the behaviour of large industrial-scale mills using the data obtained in small laboratory-scale mills. It is known that the rate of size reduction is enhanced by wet rather than dry grinding, but the degree of enhancement depends on the material being ground. Bond states that the capacity of wet grinding in the industrial scale is 1.3 times higher than dry grinding under the same operating conditions. Austin et al. showed that the ratio of the specific rate of breakage values between dry and wet grinding varied from 1.1-2.0 for different materials. The degree of this acceleration depends on the slurry concentration and the fineness of grinding. The water eliminates or reduces the effect of slowing-down due to coating of the balls and reagglomeration of fines in the mill. In addition, the water allows better transfer of the mechanical action of the tumbling balls to the stressing of the particles, leading to higher rates of breakage. On the other hand, as fines accumulate in the mill, the slurry density becomes more viscous and decrease in the breakage rate is occurred after a particular viscosity value.

This paper reports on the kinetics of dry and wet grinding of calcite, barite, quartz, lignite and anthracite, all from Turkey, and compares the results of dry grinding to those of wet grinding for these minerals and coals ground in a laboratory size ceramic ball mill.

Theory

The grinding rate constant, which is widely accepted as first-order expression of grinding rate, is one of the important parameters required to evaluate a grinding process. The normal breakage rate is defined by a first-order breakage rate as given below:

\[ \text{rate of breakage of size } i = S_i w(t) W \]  

(1)

where $S_i$ is the constant specific rate of breakage of particles of size $i$, and $w(t)$ is the mass fraction of the total charge ($W$) that is of size $i$ at time $t$ of grinding. It is common to use sieving both to prepare test feed sizes and measure particle size distributions and size $i$. 

* For correspondence (e-mail: yekeler@cumhuriyet.edu.tr)
refers to a screen interval (usually a $\sqrt{2}$ interval) indexed by $i=1$ for the largest size, 2 for the next smaller size, down to $n$ for the final size interval. On the other hand, at long grinding times, $S_i$ may decrease as finely ground material accumulates in the mill causing non-first order breakage, i.e., a slowing-down of breakage rates.

The cumulative primary breakage distribution ($B_{i,j}$) is defined as the mass fraction of material broken from the larger size $j$ that appears less than the upper size of a smaller size interval $i$ on a primary breakage action. An empirical equation for this function is as follow:

$$B_{i,j} = \left\{ \begin{array}{ll}
\left( \frac{x_i - 1}{x_j} \right)^{\gamma} + (1-\phi) \left( \frac{x_i - 1}{x_j} \right)^{\beta} & , \quad n \geq i > j \geq 1 \\
1 & , \quad i = j
\end{array} \right. \quad \ldots (2)$$

where $x_i$ is the top size of the size interval indexed by $i$. The parameters $\gamma$, $\phi$ and $\beta$ are characteristic of the material being ground. On plotting experimentally determined $B_{i,j}$ values versus $x_i$, on log-log scales, the slope of the straight line lower portion of the curve gives the value of $\gamma$, $\phi$ is the intercept of this part of the line extrapolated to $x_2$, and $\beta$ is determined to make the function fit the upper part of the curve.

**Experimental Procedure**

The feed materials used in the grinding test were -425+300 $\mu$m (40x50 mesh) sieve fractions of calcite, barite, quartz, lignite and anthracite from different regions of Turkey. These materials were prepared by crushing first in a jaw crusher then in a double roll crushe.

The grinding experiments were performed in a cylindrical ceramic ball mill of 128 mm internal diameter operated at 70% of critical speed, using ceramic balls of 25.3 mm diameter (Table 1). The Standard S and B test conditions were used to give first order grinding kinetics when steel media and mills employed: 20% mill volume filled by the ball bed (assuming a bed porosity of 0.4) and 60% of the interstices of the ball bed filled with powder. Sieving schedules were established from a study of sieving kinetics, and a sieving time of 10 min on a Rotap sieving machine with a sample of 50 g taken from the ground product (by cone and quartering) was found to be satisfactory. The grinding tests were carried out dry and wet at 1, 2, 4, 8, 16 and 32 min of grinding time.

Size analysis by sieving was performed by washing with tap water for at least 10 min starting from the top size, then each successive screen was washed in this manner, removed and put into an oven to dry. The dried material remaining on each screen was further dry sieved in a Rotap shaker for 10 min. Finally, each remaining fraction on the screen was weighed.

**Results and Discussion**

Fig. 1 shows the first-order plots of dry and wet grinding of calcite, barite, quartz, lignite and anthracite. It had been previously shown that good first order plots were only obtained for the feed sizes less than about 650 $\mu$m for the ceramic media at the given experimental conditions. For the non-first order breakage of larger sizes called abnormal breakage rate, an approximate $S$ value was experimentally obtained to be lower than the $S$ values obtained for the feed sizes less than 650 $\mu$m. This is due to larger feed sizes ground in the mill that are not nipped properly by the fixed ceramic ball sizes chosen. It is generally noted that the abnormal breakage region for steel media (25.4 mm balls) is started when larger sizes than approximately 1000 $\mu$m. In addition, a mill with lower density grinding media will have both a lower capacity (tph) and a lower power draw and specific rate of breakage.

**Table I—Test conditions**

<table>
<thead>
<tr>
<th>Mill</th>
<th>Inner diameter, mm</th>
<th>128</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length, mm</td>
<td>212</td>
<td></td>
</tr>
<tr>
<td>Volume, cm$^3$</td>
<td>2500</td>
<td></td>
</tr>
<tr>
<td>Critical speed, rpm</td>
<td>132</td>
<td></td>
</tr>
<tr>
<td>Operational speed, rpm</td>
<td>92</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Balls</th>
<th>Material</th>
<th>Ceramic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter, mm</td>
<td>25.3</td>
<td></td>
</tr>
<tr>
<td>Specific gravity</td>
<td>3.75</td>
<td></td>
</tr>
<tr>
<td>Charge, kg</td>
<td>1.125</td>
<td></td>
</tr>
<tr>
<td>Fractional ball filling</td>
<td>0.2</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material</th>
<th>Specific gravity</th>
<th>Powder weight, g</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcite</td>
<td>2.69</td>
<td>194</td>
</tr>
<tr>
<td>Barite</td>
<td>4.38</td>
<td>315</td>
</tr>
<tr>
<td>Quartz</td>
<td>2.65</td>
<td>191</td>
</tr>
<tr>
<td>Lignite</td>
<td>1.46</td>
<td>105</td>
</tr>
<tr>
<td>Anthracite</td>
<td>1.42</td>
<td>102</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Powder-ball loading ratio</th>
<th>0.60</th>
</tr>
</thead>
</table>

| Pulp density, % (by volume) | 40   |
values, giving the same comparable as one with high density balls.

The $S$, $a_T$ and $\alpha$ values for all materials studied are outlined in Table 2. The values of $S$ can be fitted to be Eq. (3) gave an $a_T$ value by inserting $\alpha$ values and $x_c = 650 \mu m$ for all materials in this work.

$$S_i = a_T \left( \frac{x_c}{x_0} \right)^\alpha$$  \hspace{1cm} (3)

The primary breakage distribution functions were determined by using the BII calculation method for grinding of calcite, barite, quartz, lignite and anthracite as shown in Fig. 2. The good $B_{ij}$ results are obtained when the time of grinding is chosen to give an amount of material broken out of the top size interval of about 20-30% (ref. 1). Thus, the method is applied to one minute of grinding time data for calcite, barite, lignite and anthracite, and 2 min of grinding time data for quartz in this study. The equation for BII calculation is as following:

$$B_{ij} = \log \left[ \frac{(1 - P_i(0))/(1 - P_i(t))}{(1 - P_j(0))/(1 - P_j(t))} \right], \quad i > 1$$  \hspace{1cm} (4)

where $P_i(0)$ = cumulative weight fraction at time 0 for size interval $i$, $P_i(t)$ = cumulative weight fraction at time $t$ for interval $i$. The results of the primary breakage distribution calculations of all materials are given in Table 3.

![Fig. 1—First-order plots for dry and wet grinding of -425+300 μm. (a) calcite, (b) barite, (c) quartz, (d) lignite and (e) anthracite.](image-url)
Fig. 2—Primary cumulative breakage distribution functions for dry and wet grinding of -425+300 μm (a) calcite, (b) barite, (c) quartz, (d) lignite and (e) anthracite.

Fig. 3—Simulated and experimental product size distributions of dry ground (a) calcite, (b) barite, (c) quartz, (d) lignite and (e) anthracite.
Fig. 4—Simulated and experimental product size distributions of wet ground (a) calcite, (b) barite, (c) quartz, (d) lignite and (e) anthracite.

Fig. 5—False time (apparent first order grinding time) versus real grinding time for dry and wet grinding of (a) calcite, (b) barite, (c) quartz, (d) lignite and (e) anthracite.
Fig. 6—Slowing-down factor ($k$) versus real grinding time for (a) calcite, (b) barite, (c) quartz, (d) lignite and (e) anthracite grinding.

Fig. 7—Slowing-down factor ($k$) versus the 80% passing size of the product for (a) calcite, (b) barite, (c) quartz, (d) lignite and (e) anthracite in the mill.
Figs 3 and 4 show the particle size distributions of dry and wet grinding of the calcite, barite, quartz, lignite and anthracite at various grinding times, respectively. The results of dry and wet grinding up to 4 min of grinding time for calcite, barite and quartz were simulated using the characteristics parameters of α, α₁, γ, φ and β in the simulation program. At longer grinding times, the simulated results were finer than the experimental results, indicating a slowing-down effect. Slowing-down effect was seen at longer grinding times for lignite and anthracite; it started at 8 min for dry lignite grinding, while it started at 16 min for wet lignite grinding. The dry grinding of anthracite reached the slowing-down effect at 4 min, the wet grinding reached the slowing-down effect at 8 min of grinding.

The slowing-down effect was treated using the false time concept by making the simulator produce a match to a specified point on the product size distribution and designating the grinding time necessary to achieve this match as the false time ω, where ω is given in Fig. 5 shows the relation between the false time and the real time of all materials. Fig. 6 gives the relationship between the slowing-down factor (κ) and the real grinding time for these minerals and coals. Differentiation of the curve in Fig. 5 gives the value of the slowing-down factor κ.

\[ \kappa = \frac{\partial \omega}{\partial t} \]  

Fig. 7 shows the relationship between the slowing-down factor κ and the 80% passing size of the particle size distribution in the mill. The grinding clearly changes its character when the material in the mill is finer than about 300 μm. However, some materials showed sharp drops in rates, as the fines accumulated in the region of 80% passing sizes of about 100-300 μm ranges, depending on the materials given in Fig. 7.

Fig. 8 shows the values of \( S_1 \) for calcite, barite and quartz minerals as a function of the γ values. As the \( S_1 \) values increase, the γ values decrease showing that faster breakage at top sizes is associated with a larger proportion of fines in the size distributions (lower γ value). This relationship was found based on these three minerals ground as dry and wet in the laboratory size ceramic mill with an inverse linear equation as given in Fig. 8. The coals did not give the same relationships as the minerals given in Fig. 8 due to having different petrographic composition and grindability characteristics from those minerals.

Conclusions

(i) The \( S_1 \) values, from higher values to lower values, were in the order of anthracite, barite, calcite, lignite and quartz. Moreover, the \( S_1 \) values for wet grinding in the first-order breakage region were higher than the dry values for those materials ground in the ceramic mill, between 1.07 to 1.28 times as high.

(ii) The \( B_{ij} \) values for wet grinding were essentially the same as the dry values, however, the γ values for wet grinding were lower than the dry γ values, which showed that wet grinding had produced more fine products in the fines distribution region for all materials.

(iii) The slowing-down effect in the mill started at 4 min of dry grinding for calcite, barite, quartz and anthracite, and 8 min for lignite. However, the wet grinding was subjected to slowing-down effect in the mill at 4 min for calcite, barite and quartz, at 16 min for lignite and at 8 min for anthracite.

(iv) The simulations of the product size distributions for both first-order breakage and slowing-down were in good agreement with the experimental data.

(v) The breakage data obtained from the laboratory size batch mill could be applied to industrial applications by choosing the scale-up mill option in the simulation program for each material studied.
(vi) Variations of $S_i$ values with the $\gamma$ value of $B_{ij}$ were found with the following relationships for calcite, barite and quartz minerals; however, the similar equation could not be obtained for anthracite and lignite. $S_i = -0.30 \gamma + 0.52$

**Nomenclature**

- $\sigma_T$ = characteristic constant, min$^{-1}$
- $B_{i1}$ = cumulative primary breakage function of size $1$: fraction broken to less than size $x_i$ in one breakage
- $i$ = integer denoting $\sqrt{2}$ size interval
- $P_i(0)$ = cumulative weight fraction of time 0 for size interval $i$
- $P_i(t)$ = cumulative weight fraction of time $t$ for interval $i$
- $P_2(t)$ = cumulative weight fraction of time $t$ for the second interval
- $P_2(0)$ = cumulative weight fraction of time 0 for the second interval
- $S_i$ = specific rate of breakage of material of size $i$, min$^{-1}$
- $t$ = time of grinding, min
- $W$ = total powder mass in the mill
- $w_i(t)$ = fraction of mill charge in size interval $i$
- $x_o$ = standard size
- $x_i$ = size of particles, mm
- $\alpha$ = characteristic constant
- $\gamma$ = characteristic constant
- $\phi$ = characteristic constant
- $\beta$ = characteristic constant
- $\theta$ = false time, min
- $\kappa$ = slowing-down factor: ratio of specific rate of breakage at time $t$ to normal specific rate of breakage at time zero

**References**