

A study on the effect of ball diameter on breakage properties of clinker and limestone

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Effect of ball diameter has been studied on the limestone and clinker samples under batch grinding conditions based on a kinetic model. Firstly, eight different mono-size fractions between 1.7 mm and 0.106 mm formed by a $\sqrt{2}$ sieve series have been prepared. Then, S_i and $B_{i,j}$ equations are determined from the size distributions at different grinding times, and the model parameters (S_b , a_T , α , γ and ϕ_j) are compared for four different ball diameters (41, 25.4, 20 and 9.5 mm). The results show that the study on the effect of ball diameter on the grinding gives more different results than other investigations. The variation in specific rate of breakage with feed size is independent of ball diameters and kind of materials.

Keywords: Ball mill, Ball size effects, Clinker, Grinding, Limestone

Comminution is extremely energy intensive, consuming 3-4% of the electricity generated worldwide, and comprising up to 70% of all energy required in a typical mineral processing plant. Considering these factors, a small gain in comminution efficiency can have a large impact on the operating cost of a plant, while conserving resource as well¹.

During the last decade there have been considerable improvements in comminution efficiency not only due to the development of machines with the ability to enhance energy utilisation, but also due to the optimal design of grinding systems and operating variables that enable more efficient use of existing machines².

In the design of grinding circuits in mineral processing plant, the Bond method is widely used to evaluate the performance and determine the powder required and mill size for a material. This method is complex and very lengthy. In addition, it is very sensitive to procedural errors. For this reason, different methods have been proposed as alternative to the Bond method by many investigators^{3,4}.

In the recent years, matrix and kinetic models have been used both in the laboratory and in the industrial areas. Kinetic model, an alternative approach, is considering comminution as a continuous process in

which the rate of breakage of particles size is proportional to the mass present in that size⁵.

The analysis of size reduction in tumbling ball mills using the concepts of specific rate of breakage and primary daughter fragment distributions have received considerable attention for more than 50 years. Austin⁶ has reviewed the advantages of this approach and the scale-up of laboratory data to full-scale mills have also been discussed in a number of papers¹⁻⁷.

The use of Portland limestone cements has many benefits, both technical and economical. The European Pre-standard prEN 197-1 identifies 2 types of Portland limestone cement containing 6-20% limestone and 21-35% limestone respectively. It is expected that the future world production and use of Portland limestone cement will be significantly extended. These materials have different grindabilities and the individual particle size distribution of each component influences the cement hydration and finally its performance⁸.

Various laboratory studies, pilot plant works and full size plant observations showed that ball diameter, as an operating variable, can affect grinding efficiency at a given output fineness.

Austin *et al.*⁹ showed typical variation in the specific rate of breakage versus particle size for various ball diameters (with a mixture of ball size, 25.4 mm and 50 mm) in a tumbling mill. The best

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estimates of the variation of B parameters for quartz show that the greater impact force of collision involving a larger ball gives a somewhat bigger proportion of fines, i.e. lower γ and higher ϕ_j . Thus, the lower specific rate of breakage due to larger balls is partially compensated by the production of a bigger proportion of fine fragments⁹.

In addition, considering a representative unit volume of mill, the rate of ball-on-ball contacts per unit time increases with the increase in ball diameter, because 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. The relation with a_T and ball diameter in a 0.6 m diameter mill were given as $a_T \propto 1/d^9$.

This paper reports a study on the comparison of the breakage parameters of clinker and limestone under the standard conditions in a small laboratory ball mill.

Theory

When breakage is occurring in an efficient manner, the breakage of a given size fraction of material usually follows a first-order law¹⁰. Thus, the breakage rate of material that is in the top size interval can be expressed as:

$$\frac{-dw_1}{dt} = S_1 w_1(t) \quad \dots (1)$$

Assuming that S_1 does not change with time (i.e. a first-order breakage process), this equation integrates to

$$\log[w_1(t)] - \log[w_1(0)] = \frac{-S_1 t}{2.3} \quad \dots (2)$$

where $w_1(t)$ is the weight fraction of the mill hold-up for size 1 at time t ; and S_1 , the specific rate of breakage. The formula proposed by Austin *et al.*⁹ for the variation of the specific rate of breakage S_i with particle size is given below:

$$S_i = a_T X_i^\alpha \quad \dots (3)$$

where X_i is the upper limits of the size interval indexed by i (mm); and a_T and α , the model parameters that depend on the properties of the material and the grinding conditions.

On breakage, particles of given size produce a set of primary daughter fragments which are mixed into

the bulk of the powder and then, in turn, have a probability of being refractured. The set of primary daughter fragments from breakage of size j can be represented by $b_{i,j}$, where $b_{i,j}$ is the fraction of size j material, which appears in size i on primary fracture, $n \geq i > j$. It is convenient to represent these values in cumulative form, as shown below:

$$B_{i,j} = \sum_{k=n}^i b_{k,j} \quad \dots (4)$$

where $B_{i,j}$ is the sum fraction of material less than the upper size of size interval i resulting from primary breakage of size j material: $b_{i,j} = B_{i,j} - B_{i+1,j}$. Austin *et al.*⁷ have shown that the values of $B_{i,j}$ can be estimated from a size analysis of the product from short time grinding of a starting mill charge predominantly in size j (the one-size fraction *BII* method). The equation used is given below:

$$B_{i,j} = \frac{\log[(1 - P_i(0))]/\log[(1 - P_i(t))]}{\log[(1 - P_{j+1}(0))]/\log[(1 - P_{j+1}(t))]} \quad n \geq i \geq j+1 \quad \dots (5)$$

where $P_i(t)$ is the fraction by weight in the mill charge less than size X_i at time t . $B_{i,j}$ can be fitted to an empirical function¹⁰, as shown below:

$$B_{i,j} = \phi_j [X_{i-1}/X_j]^{\gamma} + (1 - \phi_j) [X_{i-1}/X_j]^{\beta} \quad n \geq i > j \quad \dots (6)$$

Where

$$\phi_j = \phi_1 [X_i/X_1]^{-\delta}; \text{ and} \quad \dots (7)$$

δ , ϕ , γ , and β are the model parameters that depend on the properties of the material. It is found that B functions are the same for different ball filling ratios, mill diameters, etc.⁹. If $B_{i,j}$ values are independent of the initial size, i.e. dimensionally normalizable, then δ is zero.

Experimental Procedure

Materials

Limestone and clinker samples, taken from Göltaş Cement Factory (Isparta/Turkey), were used as the experimental materials. Chemical properties of limestone and clinker samples are presented in Table 1. Each sample was carried out for grinding after drying at 105°C.

Table 1—Chemical composites of clinker and limestone samples

Oxides	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃
Limestone, %	10.60	1.07	0.59	48.99	1.11	-
Clinker, %	22.22	3.61	3.30	67.44	1.80	1.50

Table 2—Standard set of grinding conditions

Mill	Diameter (<i>D</i>), mm	200				
	Length, mm	200				
	Volume, cm ³	6280				
Mill speed	Critical (<i>N_c</i>) ^a , rpm	97,	100,	101,	106	
	Operational ($\phi_c = 75\%$), rpm	72,	75,	76,	80	
	Balls	Diameter (<i>d</i>), mm	9.5,	20,	25.4,	41
		Specific gravity	7.8			
Material	Quality	Alloy Steel				
	Assumed porosity, %	40				
	Ball filling volume fraction (<i>J</i> %) ^b	20				
	Specific gravity	Clinker 3.0,		Limestone 2.69		
	Powder filling volume fraction (<i>f_c</i> , %) ^c	4.2				
Interstitial filling (<i>U</i> %) ^d		52.5				

$$N_c = 42.3/\sqrt{D-d} \quad (D \text{ and } d \text{ in meter})$$

$$J = \left(\frac{\text{Mass of balls / Specific gravity of balls}}{\text{Mill volume}} \right) \times \frac{1.0}{0.6}$$

$$f_c = \left(\frac{\text{Mass of powder / Specific gravity of powder}}{\text{Mill volume}} \right) \times \frac{1.0}{0.6}$$

$$U = \frac{f_c}{0.4J}$$

Grinding tests

Firstly, Standard Bond Work Index tests were carried out for limestone and clinker samples and, the bond work index values for both the samples are found to be 13.52 kWh/t and 13.69 kWh/t respectively.

The standard set of grinding conditions used is shown in Table 2. Eight mono-size fractions (-1.7+1.18, -1.18+0.850, -0.850+0.600, -0.600+0.425, -0.425 +0.300, -0.300+ 0.212, -0.212+0.150, -0.150+0.106 mm) were prepared and ground batch-wise in a laboratory-scale ball mill for the determination of breakage functions. Each sample was taken out of the mill and, it was dry sieve for product size analysis.

Result and Discussion

Determination of S function

Typical first-order plots (*d*= 20 mm) for various feed sizes of limestone and clinker samples are shown

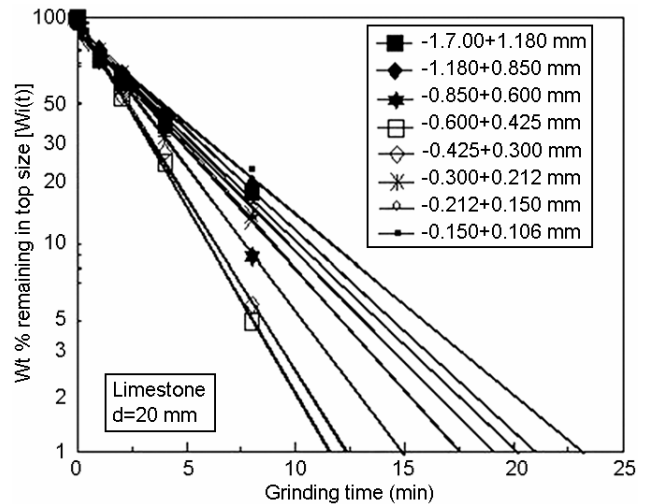


Fig. 1—First-order plots for 20 mm ball diameter of limestone

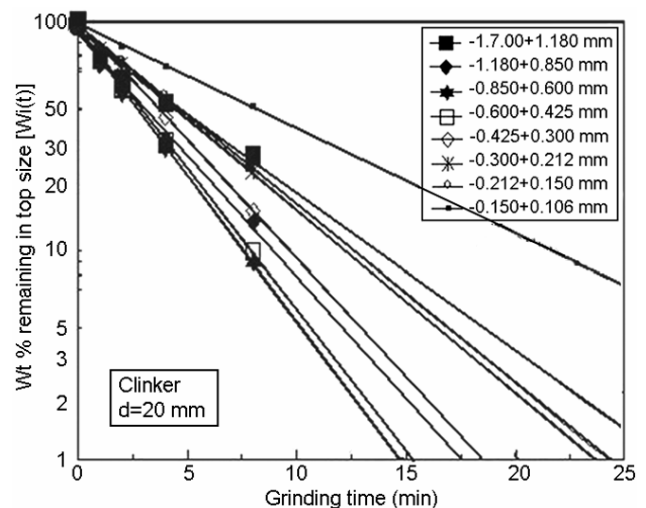


Fig. 2—First-order plots for 20 mm ball diameter of clinker

in Figures 1 and 2. Similar results are also obtained for other ball diameters of limestone and clinker samples. The results indicate that for grinding of all size fractions, two samples could be described by the first-order law. In addition, parameters of specific rate of breakage to supply by first-order plots are given in Table 3. The specific rates of breakage of each mono-size fraction that exhibits first-order grinding kinetic behaviour are determined from the slope of straight-line of first-order plots. The values of *S_i* for grinding of the four different ball size studied, as a function of size, are shown in Figures 3 and 4.

Determination of B function

By definition, the values of *B_{i,j}* are determined from the size distributions at short grinding times. The parameters are determined according to the *BII* method⁹,

Table 3—Model parameter values for different ball diameters

Ball diameter d , mm	Limestone					Clinker				
	-0.850+0.600 mm S_i (1/min)	α	a_T	γ	ϕ_j	-0.850+0.600 mm S_i (1/min)	α	a_T	γ	ϕ_j
9.5	0.028	-	0.02	0.69	0.23	0.045	2.37	0.03	0.30	0.35
20	0.307	0.60	0.27	0.70	0.25	0.308	1.00	0.28	0.67	0.28
25.4	0.400	0.61	0.41	0.71	0.32	0.366	1.22	0.39	0.68	0.26
41	0.416	1.09	0.45	1.07	0.51	0.517	0.99	0.52	0.69	0.24

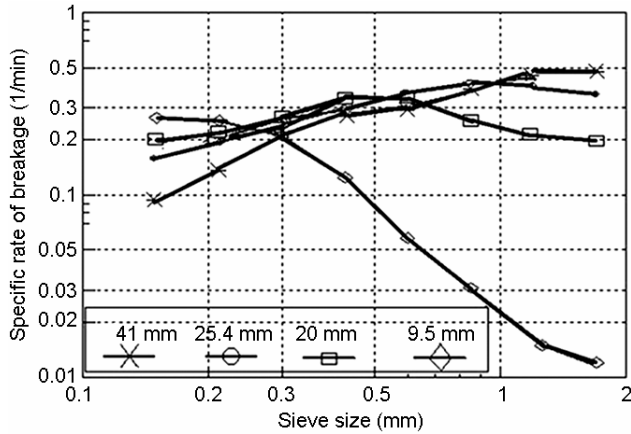


Fig. 3—Specific rates of breakage for ball diameters with 41, 25.4, 20 and 9.5 mm of limestone

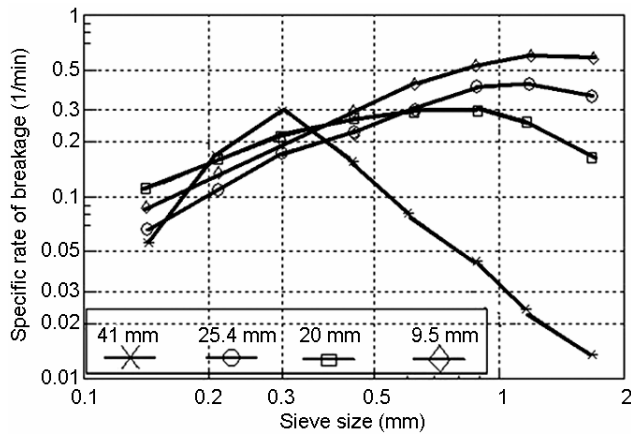


Fig. 4—Specific rates of breakage for ball diameter of 41, 25.4, 20 and 9.5 mm of clinker

and the graphical representations are shown in Figures 5 and 6. Limestone and clinker samples show a typical normalised behaviour, and the progeny distribution does not depend on the particle size, it shows that the parameter δ is zero. Model parameters supplies by cumulative distribution are given in Table 3.

Variation of breakage parameters with ball diameter

Austin *et al.*⁹ demonstrated that the specific rates of smaller sizes are higher for smaller ball diameters. The relationship with a_T and ball diameter gives

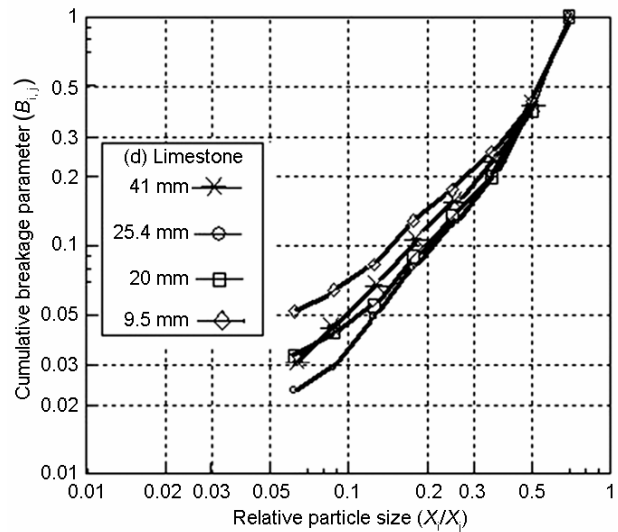


Fig. 5—Cumulative breakage distribution functions for ball diameter of 41, 25.4, 20 and 9.5 mm of limestone

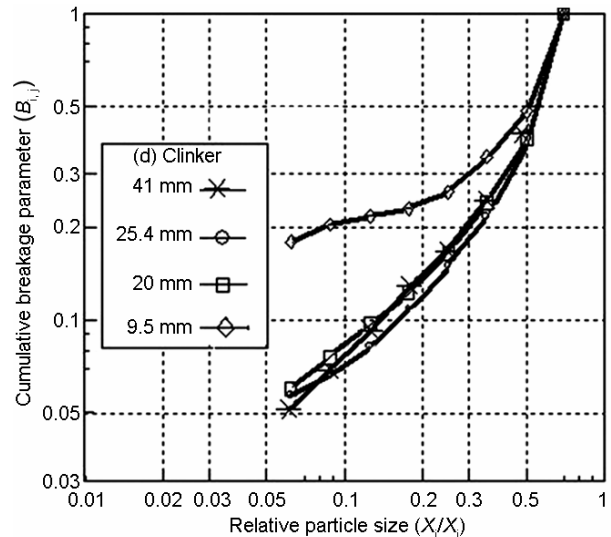


Fig. 6—Cumulative breakage distribution functions for ball diameter of 41, 25.4, 20 and 9.5 mm of clinker

$a_T \propto 1/d$. For this, variations in specific rate of breakage with ball diameter for limestone and clinker samples have been investigated. As shown in Figs 3 and 4, the specific rate of breakage (S_i) decreases with respect to increases ball size (d) for small values of particle size

(-0.300 mm). However, S_i values increase with respect to increase ball size (d) for higher values of particle size (+0.300 mm).

With respect to ball size, Kelsall *et al.*¹¹ reported no effect on $B_{i,j}$; but later Austin *et al.*¹² demonstrated that for quartz, $B_{i,j}$ alters in a systematic manner expressed in terms of γ and ϕ_j , with β remaining unchanged. It appears that the greater impact force of a collision involving a larger ball size gives a somewhat bigger proportion of fines, that is, γ is lower and ϕ_j is higher¹¹⁻¹³.

As different from the other researches, this study demonstrates that γ values of limestone and clinker samples increase with respect to increasing ball size. Therefore, proportion of fine particles decreases, that is, ball filling volume fraction ($J=0.2$) is low and very fine particles are lost among larger balls.

ϕ_j values of limestone samples increases with respect to increased ball size as similar to the results obtained by Austin *et al.*¹². However, ϕ_j values of clinker sample decrease with respect to increased ball size, because clinker is formed as an artificial material. In other words, clinkers are produced for making artificial stone (mineral) with a process, which is partial melting of mixed limestone and clay, heated to $\sim 1500^\circ\text{C}$ in a rotary kiln.

Conclusion

Dry grinding of size intervals of limestone and clinker samples shows that these samples follow the first-order breakage law with constant normalised primary breakage distributions. In addition, these samples do not depend on the particle size.

The values of the primary daughter fragment distributions and the values of α in $S_i = a_T X^\alpha$ are found to be different in both limestone and clinker.

This means that the size distribution is produced from the more different materials. As the amount of S_i or a_T values increases, it expresses more effective breakage and breaks very fast in the undersize of original particle size. According to experimentally obtained a_T values, grinding is faster with respect to increased ball diameter for every two samples.

Although, limestone and clinker samples have close work index values (13.53 kWh/t and 13.69 kWh/t), they have demonstrated entirely different characteristics in the selection function and the breakage function models.

This study shows that grinding kinetic parameters could be different for different ball diameters. Therefore, it appears that the grinding kinetics for each material must be evaluated in order to lower the energy costs in grinding process.

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