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The effect of mill speed on kinetic breakage parameters of clinker and limestone

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Abstract

In this study, the effect of mill speed was investigated on the limestone and the clinker samples of Göltaş Cement Factory (Isparta, Turkey) at batch grinding conditions based on a kinetic model. For this purpose, first, six different monosize fractions were carried out between 0.850 and 0.106 mm formed by a two-sieve series. Then, S_i and $B_{i,j}$ equations were determined from the size distributions at different grinding times, and the model parameters (S_i, a_T,α,γ, and ϕ_j) were compared for five different mill speed (fractional of mill critical speed; 55%, 65%, 75%, 85%, and 95%).

The effect of the fraction of mill critical speed (ϕ_c) on the grinding for model parameter a_T was found to be different for two different samples: $a_T = 0.0344 \exp(0.00301\ \phi_c)$ for clinker and $a_T = 0.0225 \exp(0.06183\ \phi_c)$ for limestone. Additionally, it was found in this study that optimum grinding occurs at $\phi_c = 85\%$, in contrast to the 70% of critical speed of the ball mill in the cement factory.

Keywords: Grinding; Clinker; Limestone

1. Introduction

Comminution is extremely energy-intensive, consuming 3% to 4% of the electricity generated worldwide and comprising up to 70% of all energy required in a typical cement plant [1]. 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 well.

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 machines [2].

In the design of grinding circuits in a cement plant, the Bond method is widely used to evaluate the performance and determine the power required and the mill size for a material. This method is complex, and it takes a very long time. In addition, it is very sensitive to procedural errors. For this reason, different methods have been proposed as an alternative to the Bond method by many investigators.

In the recent years, the matrix model and kinetic model, which are suggested by investigators, have been used in laboratories and industrial areas. The kinetic model, which is an alternative approach, considers comminution as a continuous process in which the rate of the breakage of particle size is proportional to the mass present in that size.

The analysis of size reduction in tumbling ball mills using the concepts of specific rate of breakage and primary daughter fragment distribution has received considerable attention in the last years. Austin et al. [3] has reviewed the advantages of this approach, and the scale-up of laboratory data on full-scale mills have also been discussed in a number of papers.

The use of Portland limestone cements has many benefits, both technical and economical. The European Prestandard prEN 197-1 identifies two 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 grind-

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Table 1
Chemical composition of clinker and limestone

Oxides	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	SO_3 (%)	LOI (%)
Limestone	10.60	1.07	0.59	48.99	1.11	–	38.72
Clinker	22.22	3.61	3.30	67.44	1.80	1.50	0.11

LOI—Loss of ignition.

abilities, and the individual particle size distribution of each component influences the cement hydration and ultimately its performance [4].

Various laboratory studies, pilot plant works, and full-size-plant observations showed that the mill speed, which is an operating variable, can affect grinding efficiency at a given output fineness.

The normal specific rates of breakage vary with mill speed in the same way. However, the maximum in power occurs at different fractions of critical speed from one mill to another, depending on the mill diameter, the type of lifters, the ratio of ball-to-mill diameter, and the ball and powder filling conditions. The maximum is usually found within the range of 70–85% of critical speed. Within the range of speed near the maximum, the power drawn are relatively small changes in the normal specific breakage rates with rotational speed. There is no significant variation in B values with mill speed within this range [5].

The change from cascading to cataracting pattern is the cause of the peak of feed size specific rate of breakage S_i under the conditions of ball-filling volume fraction $J=0.5$ and interstitial filling $U=1$ in dry batch grinding of dolomite [6]. For these conditions, and with the eight 0.25-in. lifter bars on the 10-in.-diameter shell, the change occurred at a fraction of mill critical speed, $\phi_c=75\%$. Furthermore, the change to cataracting is accompanied by a reduction in S_1, and hence, cascading is the major action within the mill for the conditions stated.

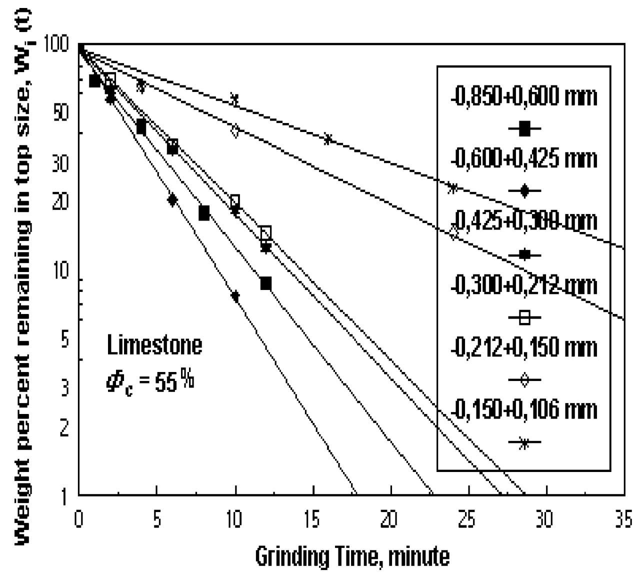

Fig. 1. First-order plots for $\phi_c=55\%$ of limestone.

Austin and Brame [7] have attempted to quantify the correction to kinetic model parameter a_T in Eq. (1) and hence to S, for mill critical speed by

$$a_T \propto (\phi_c - 0.1)/\{1 + \exp[15.7(\phi_c - 0.94)]\} \qquad (1)$$

This paper presents a comparison of the breakage parameters with mill speed under the standard conditions in a small laboratory ball mill of clinker and limestone samples,

Table 2
Grinding conditions

Mill	Diameter, D (mm)	200
	Length (mm)	200
	Volume (cm^3)	6283
Mill speed	Critical, N_c (rpm)[a]	101
	Operational, ϕ_c (%)	55 65 75 85 95
Grinding media (balls)	Diameter, d (mm)	25.4
	Specific gravity (g/cm^3)	7.8
	Quality	Alloy steel
	Assumed porosity (%)	40
	Ball-filling volume fraction, J (%)[b]	20
Material	Specific gravity (g/cm^3)	Clinker: 3.0; limestone: 2.69
	Powder-filling volume fraction, f_c (%)[c]	4.2
	Interstitial filling, U (%)[d]	52.5

[a] Calculated from $N_c = 42.3/\sqrt{D-d}$ (D, d in meters).
[b] Calculated from J=(((mass of balls)/(ball density))/(mill volume))×((1.0)/(0.6)).
[c] Calculated from f_c=(((mass of powder)/(formal bulk density))/(mill volume)).
[d] Calculated from $U = \frac{f_c}{0.4\,J}$.

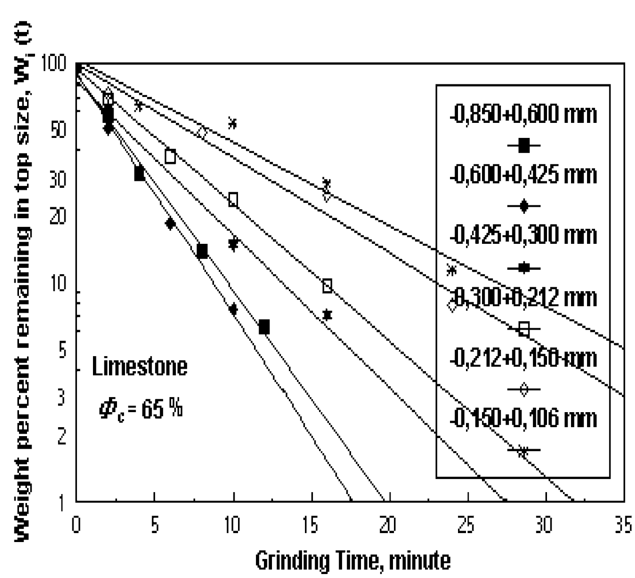

Fig. 2. First-order plots for $\phi_c=65\%$ of limestone.

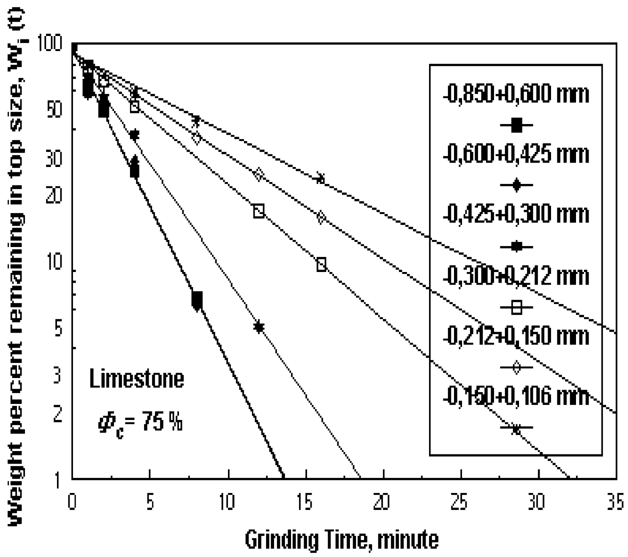

Fig. 3. First-order plots for $\phi_c = 75\%$ of limestone.

which are ground at the condition 70% of critical speed of cement ball mill in Göltaş Cement Factory.

2. Theory

When breakage is occurring in an efficient manner, the breakage of a given size fraction of material usually follows a first-order law [8]. Thus, the breakage rate of material that is in the top size interval can be expressed as

$$\frac{-\mathrm{d}w_1}{\mathrm{d}t} = S_1 w_1(t) \quad (2)$$

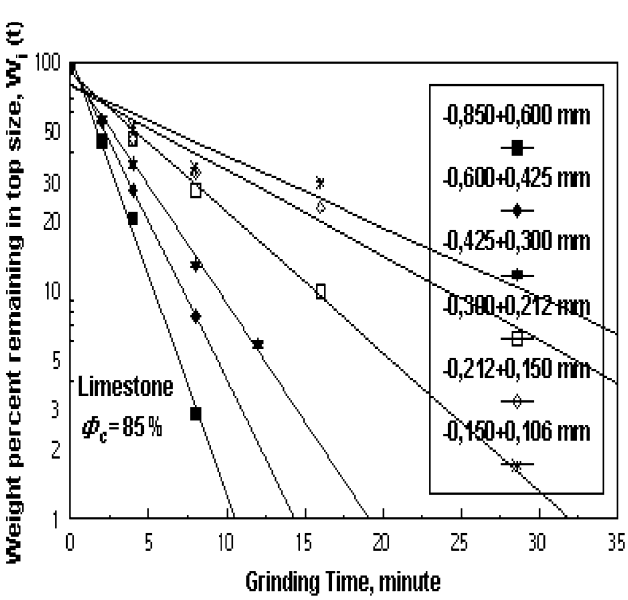

Fig. 4. First-order plots for $\phi_c = 85\%$ of limestone.

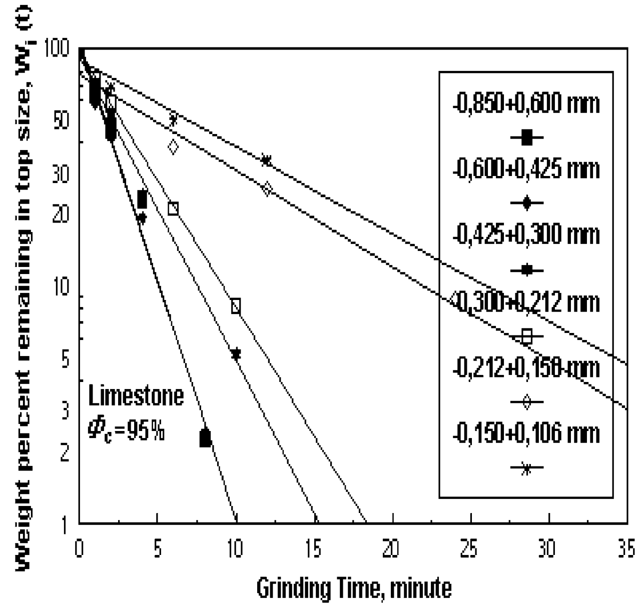

Fig. 5. First-order plots for $\phi_c = 95\%$ of limestone.

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

$$\log(w_1(t)) - \log(w_1(0)) = \frac{-S_1 t}{2.3} \quad (3)$$

where $w_1(t)$ is the weight fraction of the mill hold-up that is of size 1 at time t, and S_1 is the specific rate of breakage. The formula proposed by Austin et al. [5] for the variation of the specific rate of breakage S_i with particle size is

$$S_i = a_T X_i^{\alpha} \quad (4)$$

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

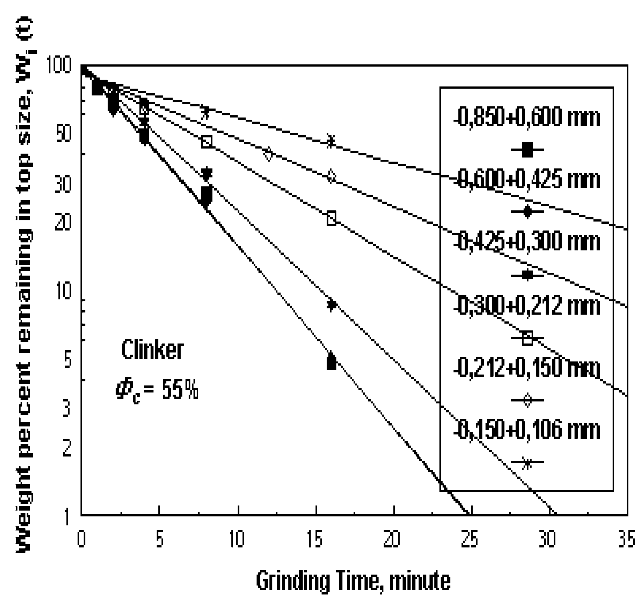

Fig. 6. First-order plots for $\phi_c = 55\%$ of clinker.

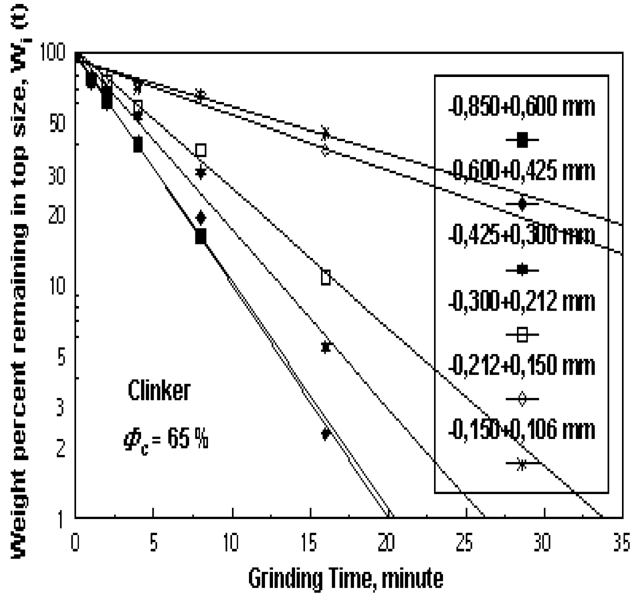

Fig. 7. First-order plots for $\phi_c = 65\%$ of clinker.

On breakage, particles of a given size produce a set of primary daughter fragments, which are mixed into the bulk of the powder and would 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.

$$B_{i,j} = \sum_{k=n}^{i} b_{k,j} \quad (5)$$

where $B_{i,j}$ is the sum fraction of material less than the upper size of size interval *i*, resulting from primary breakage of

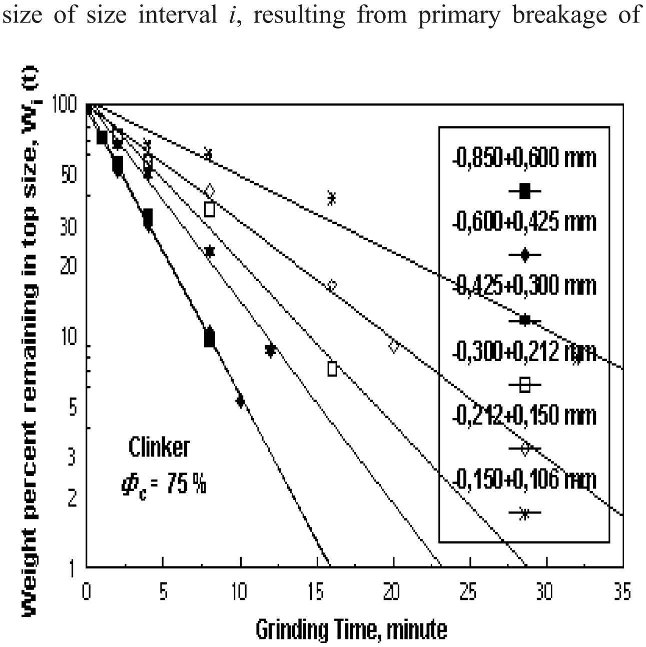

Fig. 8. First-order plots for $\phi_c = 75\%$ of clinker.

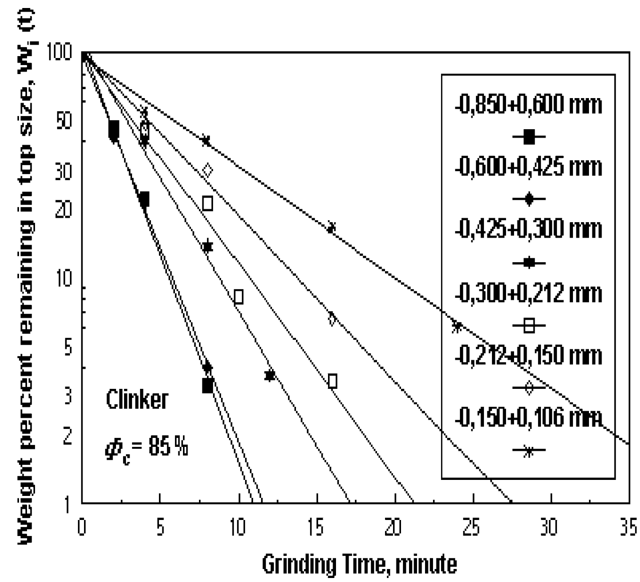

Fig. 9. First-order plots for $\phi_c = 85\%$ of clinker.

size *j* material: $b_{i,j} = B_{i,j} - B_{i+1,j}$. Austin et al. [3] 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

$$B_{i,j} = \frac{\log[(1 - P_i(0))]/\log[(1 - P_i(t))]}{\log[(1 - P_{j+1}(0))]/\log[(1 - P_{j+1}(t))]}. \qquad n \leq i \leq j+1 \quad (6)$$

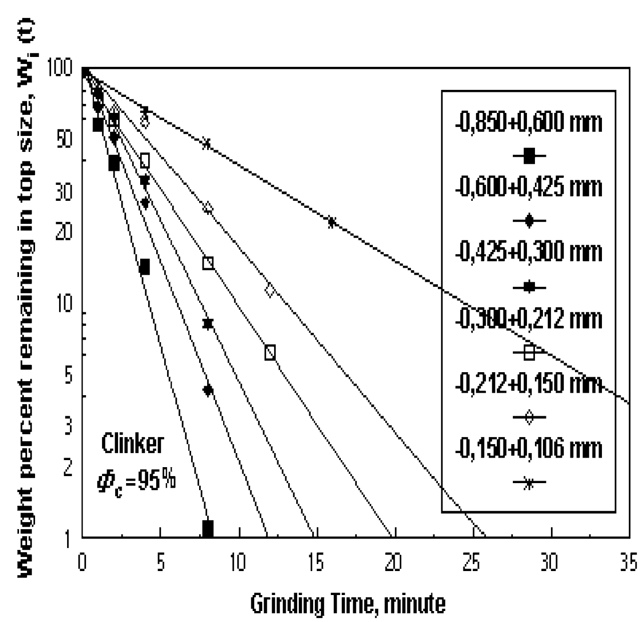

Fig. 10. First-order plots for $\phi_c = 95\%$ of clinker.

Table 3
Model parameter values of limestone

ϕ_c (%)	−0.300+0.212 (mm) Si	α	a_T	ϕ_j	γ
55	0.139	0.831	0.199	0.507	1.315
65	0.141	0.765	0.273	0.510	1.336
75	0.142	0.752	0.371	0.514	1.357
85	0.150	0.833	0.436	0.504	1.432
95	0.220	1.278	0.489	0.497	1.237

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 function [9].

$$B_{i,j} = \phi_j[X_{i-1}/X_j]^{\gamma} + (1-\phi_j)[X_{i-1}/X_j]^{\beta} \qquad n \leq i \rangle j \tag{7}$$

where

$$\phi_j = \phi_1[X_i/X_1]^{-\delta} \tag{8}$$

where δ, ϕ, γ, and β are 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. [5]. If $B_{i,j}$ values are independent of the initial size, i.e., dimensionally normalizable, then δ is zero.

3. Experimental part

3.1. Material

Limestone and clinker samples taken from Göltaş Cement Factory were used as the experimental materials. The chemical compositions of the limestone and the clinker samples are presented in Table 1.

3.2. Grinding tests

Firstly, Standard Bond Work index tests were made for limestone and clinker samples. The Bond Work index values of limestone and clinker samples were determined as 13.52 and 13.69 kWh/t, respectively. The standard set of grinding conditions used is shown in Table 2 for a laboratory mill with a 6283-cm^3 volume. Six monosize fractions (−0.850+0.600, −0.600+0.425, −0.425+0.300, −0.300+0.212, −0.212+0.150, and −0.150+0.106 mm) were prepared and ground batch-wise (grinding time: 1, 2, 4, 8, 12, 16, and 18 min) in a laboratory-scale ball mill for determination of the breakage functions. Each sample was taken out of the mill and dry-sieved for size analysis.

Table 4
Model parameter values of clinker

ϕ_c (%)	−0.300+0.212 (mm) Si	α	a_T	ϕ_j	γ
55	0.095	1.261	0.191	0.419	0.801
65	0.137	1.314	0.234	0.415	0.809
75	0.162	1.249	0.301	0.413	0.848
85	0.217	1.241	0.462	0.394	0.857
95	0.230	1.272	0.611	0.387	1.081

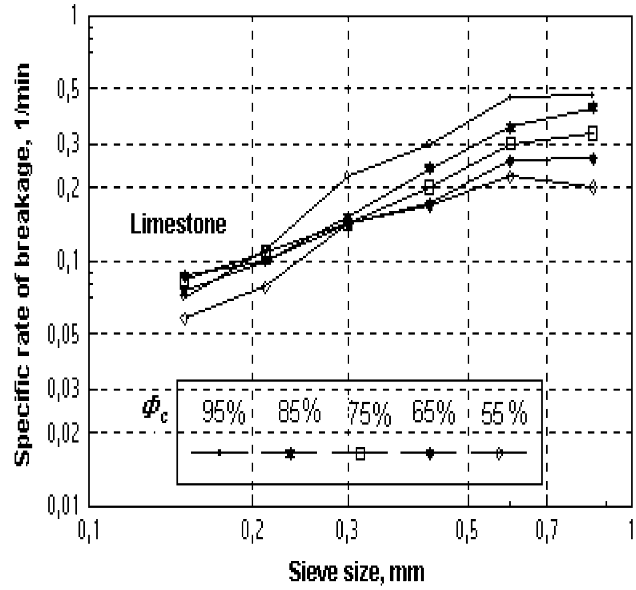

Fig. 11. Specific rate of breakage for limestone.

4. Results and discussion

4.1. Determination of S parameters

The first-order plots for the various feed sizes of limestone and clinker samples are given in Figs. 1–10. The results indicated that breakage generally follows the first-order relation, and values of S_i could be determined from the slope of straight line of first-order plots (Tables 3 and 4). In addition, Figs. 11 and 12 show the S_i in relation to the

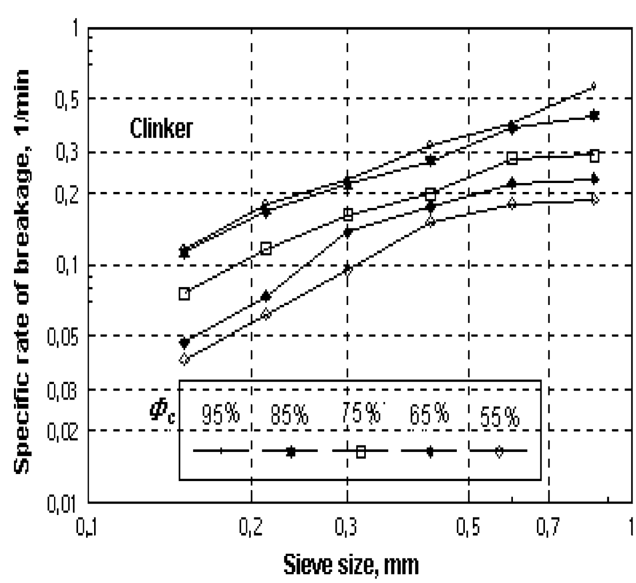

Fig. 12. Specific rate of breakage for clinker.

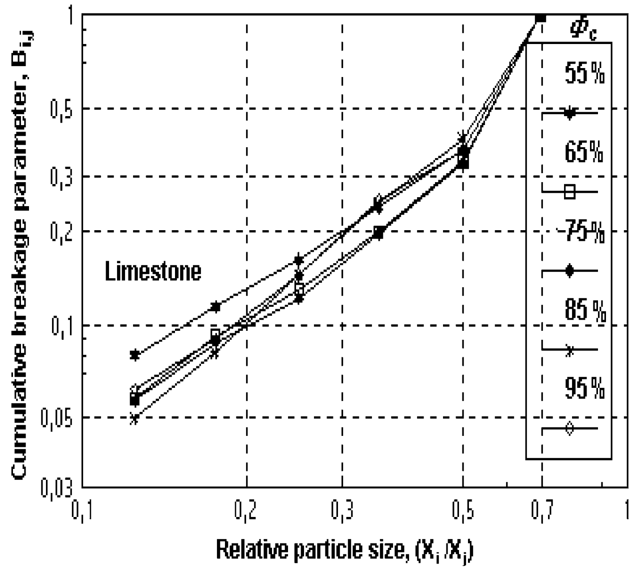

Fig. 13. Cumulative breakage distribution function for limestone.

fraction of mill critical speed and particle size for limestone and clinker, respectively.

The dry-grinding of size intervals of limestone and clinker samples showed that both samples followed the first-order breakage law with constant normalized primary breakage distributions. The values of the primary daughter fragment distributions and the values of α in $S_i = a_T X^{\alpha}$ were different in the limestone and the clinker. As the amount of S_i or a_T values increase, the effective breakage increases, resulting in breaking quickly to the undersize of original particle size. The experimental a_T values show that grinding is faster for both samples as the fraction of mill critical speed increases. However, clinker grinds faster of original particle size than limestone.

Herbst and Fuerstenau [6] showed that the change from cascading to cataracting pattern was the cause of peak in

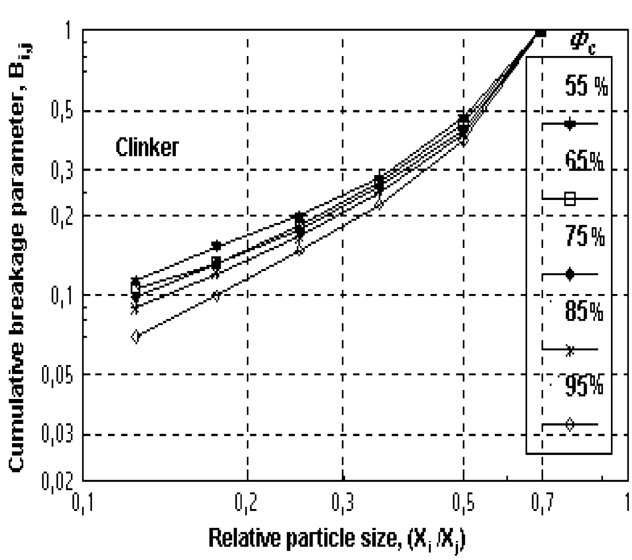

Fig. 14. Cumulative breakage distribution functions for clinker.

Table 5
$B_{i,1}$ values of clinker

Sieve size (mm)	$\phi_c = 55\%$	$\phi_c = 65\%$	$\phi_c = 75\%$	$\phi_c = 85\%$	$\phi_c = 95\%$
− 0.850 + 0.600	1	1	1	1	1
− 0.600 + 0.425	0.468	0.442	0.422	0.404	0.386
− 0.425 + 0.300	0.277	0.268	0.259	0.246	0.221
− 0.300 + 0.212	0.192	0.182	0.176	0.166	0.148
− 0.212 + 0150	0.153	0.133	0.130	0.121	0.100
− 0.150 + 0.106	0.113	0.107	0.098	0.090	0.067

the feed size dependence on the specific rate of breakage S_i, which occurred at $\phi_c = 75\%$ in their study. The present study showed that change from cascading to cataracting pattern occurred at $\phi_c = 85\%$. Therefore, the present results indicate that results were found to be different than that of Herbst and Fuerstenau [6]. The value of ϕ_c might depend on the difference in the mineralogical characteristic of the samples.

4.2. Determination of B parameters

The values of B were determined from the size distributions at short grinding times using BII method and are shown in Figs. 13 and 14. The results of limestone and clinker samples showed a typical normalized behaviour, so that the progeny distribution did not depend on the feed particle size, and the kinetic model parameter δ was zero. The model parameters are also given in Tables 3 and 4.

It can be seen from the data in Tables 3 and 4 that model parameter values of the mill speed is similar to the literature on the critical speed. The ϕ_j values show a decrease for both samples with increasing mill speed. However, γ values tend to increase with the increase in the mill speed for clinker. It tends to increase up to $\phi_c = 85\%$ of mill critical speed and then start to show a decreasing trend after $\phi_c = 85\%$ for limestone. Therefore, the maximum of γ was found to be about 85% of critical speed.

Austin et al. [5] demonstrated that the variation of B values does not have a significant effect on the mill speed. In contrast, the present work shows a significant variation of B values with mill speed. The $B_{i,j}$ values for grinding are different for limestone and clinker (Tables 5 and 6). The γ value of clinker is lower than that of limestone (γ = from 0.801 to 1.081 for clinker; γ = from 1.231 to 1.431 for limestone), which emphasizes that the grinding of clinker produces finer material than the limestone grinding.

Table 6
$B_{i,1}$ values of limestone

Sieve size (mm)	$\phi_c = 55\%$	$\phi_c = 65\%$	$\phi_c = 75\%$	$\phi_c = 85\%$	$\phi_c = 95\%$
− 0.850 + 0.600	1	1	1	1	1
− 0.600 + 0.425	0.366	0.339	0.333	0.401	0.366
− 0.425 + 0.300	0.241	0.201	0.198	0.247	0.254
− 0.300 + 0.212	0.163	0.130	0.122	0.145	0.145
− 0.212 + 0150	0.115	0.092	0.088	0.082	0.090
− 0.150 + 0.106	0.080	0.058	0.057	0.050	0.062

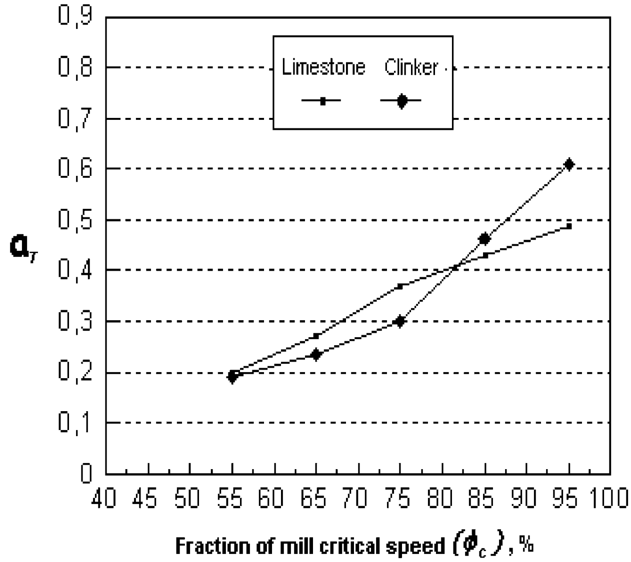

Fig. 15. Variation of a_T with fraction of critical mill speed.

4.3. Variation of a_T values with fraction of mill critical speed

The variation of a_T with mill speed has been formulated by Austin and Brame [7], as given in Eq. (1). Similarly, in this study, variation Eqs. (9) and (10) were formulated using Fig. 15, which shows the variation of a_T values with the fraction of mill critical speed for both samples. The formulations of this present work are different from Austin and Brame [7].

$$\text{For Clinker}: \quad a_T = 0.0344 \exp(0.00301\ \phi_c) \qquad r^2 = 0.98 \tag{9}$$

$$\text{For Limestone}; \quad a_T = 0.0225 \exp(0.06183\ \phi_c) \quad r^2 = 0.96 \tag{10}$$

It can be seen from Fig. 15 that the a_T value of clinker is higher than of limestone (a_T = from 0.199 to 0.489 for limestone; a_T = from 0.191 to 0.611 for clinker). This indicates that clinker grinds faster of original particle size than limestone because clinker was formed by thermal processing as an artificial sample [10].

5. Conclusions

Although limestone and clinker samples have close work index values 13.53 and 13.69 kWh/t, respectively, they have demonstrated entirely different characteristics in the selection function and the breakage function model parameters. In addition, these samples do not depend on the particle size from cumulative breakage distribution function.

In this study, it was found that optimum grinding occurs at 85% of critical speed, compared to the optimum grinding at 70% of critical speed of the ball mill in the cement factory. The variation of a_T values with the fraction of mill critical speed (ϕ_c) gave high correlation coefficients of 0.98 and 0.96 for clinker and limestone, respectively, through a regression analysis.

This study showed that grinding kinetic parameters could be different for clinker and limestone. Therefore, it has appeared that the grinding kinetics for each material must be evaluated to lower the energy costs in the grinding process.

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