Pergamon

Cement and Concrete Research 33 (2003) 439–445

CEMENT AND CONCRETE RESEARCH

A study on the specific rate of breakage of cement materials in a laboratory ball mill

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Received 9 April 2002; accepted 26 August 2002

Abstract

The specific rate of breakage (S_i) in the widely accepted first-order expression of grinding rate is one of the important factors required to evaluate a grinding process, particularly for the initial grinding stage in various mill types.

In this study, the effects of ball diameter and feed size on the specific rate of breakage were investigated on limestone, trass and clinker samples at batch grinding conditions based on a kinetic model. Eight different monosize fractions were prepared between 1.7 and 0.106 mm, using a $\sqrt{2}$ sieve series. The specific rates of breakage (S_i) were determined from the size distributions at different grinding times, and the specific rates of breakage were compared for three different ball diameters (41, 25.4 and 9.5 mm).

The results indicated that the variation of the specific rate of breakage with feed size of cement materials could be expressed. For the specific rate of breakage of each material, empirical equations were developed to express it as a function of feed size and ball diameter.

Keywords: Grinding; Clinker; Limestone; Trass

1. Introduction

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 resources as well [1].

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].

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

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

Table 1
Chemical composition of samples using in experiments

	Limestone	Trass	Clinker
SiO_2 (%)	10.60	58.82	22.22
Al_2O_3 (%)	1.07	17.78	3.61
Fe_2O_3 (%)	0.59	3.91	3.30
CaO (%)	48.99	4.12	66.44
MgO (%)	1.11	0.11	1.80
SO_3 (%)	–	–	1.50
Loss on ignition (%)	36.56	3.66	1.05

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0008-8846/02/$ – see front matter
PII: S0008-8846(02)00976-6

Table 2
The standard set of grinding conditions

Mill	Diameter and length		200 mm	
	Volume		6280 cm^3	
Mill	Critical	97 rpm	101 rpm	105 rpm
Speed	Operational ($\phi_c = 75\%$)	72 rpm	76 rpm	79 rpm
Balls	Diameter	9.5 mm	25.4 mm	41 mm
	Specific gravity, g/cm^3		7.8	
	Assumed porosity		40%	
	Ball filling volume fraction (J)		20% ($J = 0.2$)	
Material	Specific gravity, g/cm^3	Clinker; 3.0	Trass; 2.33	Limestone; 2.69
	Interstitial filling (U)		52.5% ($U = 0.525$)	
	Powder filling volume (f_c)		4.2% ($f_c = 0.042$)	

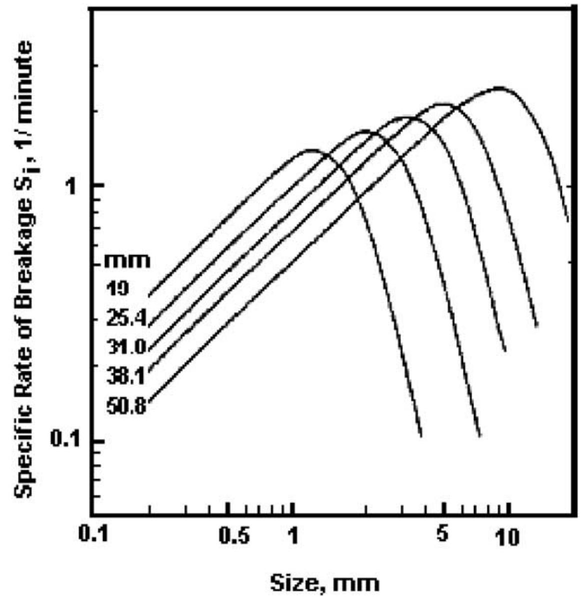

Fig. 1. Variation of specific rate of breakage versus particle size for ball diameters [4].

Austin et al. show that typical variation of the specific rate of breakage vs. particle size for various ball diameters in a tumbling mill follows the trends shown in Fig. 1. Additionally, considering a representative unit volume of mill, the rate of ball-on-ball contacts per unit time will increase as ball diameter decreases, 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. Fig. 2 shows the effect of ball diameter in a 0.6-m diameter mill, which gives the relation $a_T \propto 1/d$ [4].

This paper presents the effects of ball diameter and feed size on the specific rate of breakage of clinker, trass and limestone determined under standard conditions in a small laboratory ball mill.

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 [5]. Thus, breakage rate of material, which is in the top size interval, can be expressed as:

$$\frac{-\mathrm{d}w_1}{\mathrm{d}t} = S_1 w_1(t) \tag{1}$$

Table 3
Values of constants in Eq. (12)

Material	C_1	C_2	m	n	α
Limestone	1.31	294	− 1.48	1.725	1.01
Trass	30.96	20	− 0.781	0.962	1.33
Clinker	12.86	50	− 0.736	1.217	1.01

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

$$\log(w_1(t)) - \log(w_1(0)) = \frac{-S_1 t}{2.3} \tag{2}$$

where $w_1(t)$ and $w_1(0)$ are the weight fraction of the mill hold-up that is of size 1 at time t and 0, respectively; S_1 is

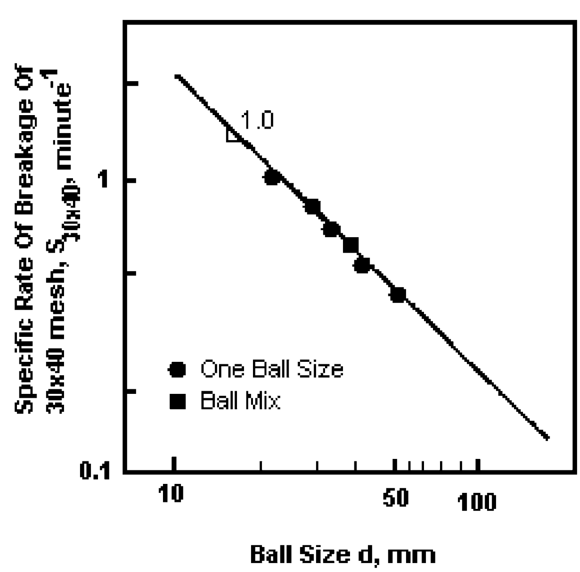

Fig. 2. Variation of specific rate of breakage with ball diameter [4].

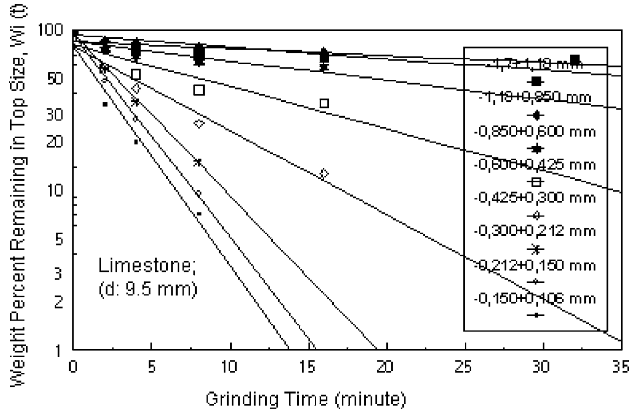

Fig. 3. First-order plots for 9.5-mm ball diameter of limestone.

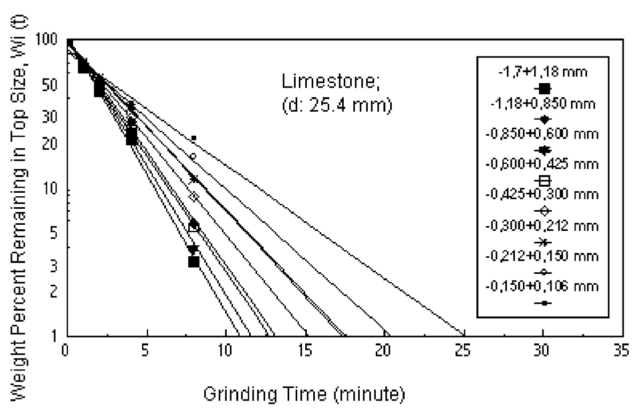

Fig. 4. First-order plots for 25.4-mm ball diameter of limestone.

the specific rate of breakage mathematical formula proposed by Austin and Bagga [5]; for the variation of the specific rate of breakage, S_i with particle size is:

$$S_i = a_T X_i^{\alpha} \tag{3}$$

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

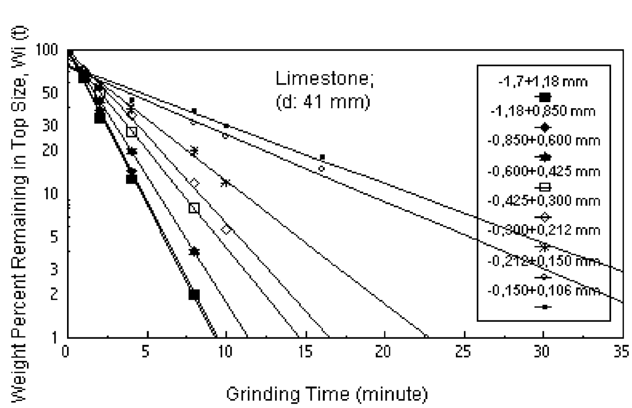

Fig. 5. First-order plots for 41-mm ball diameter of limestone.

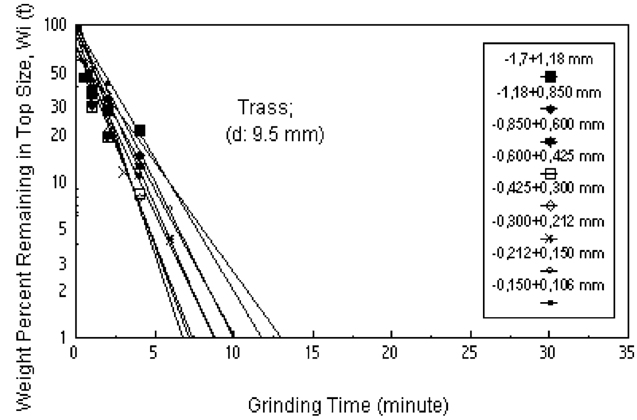

Fig. 6. First-order plots for 9.5-mm ball diameter of trass.

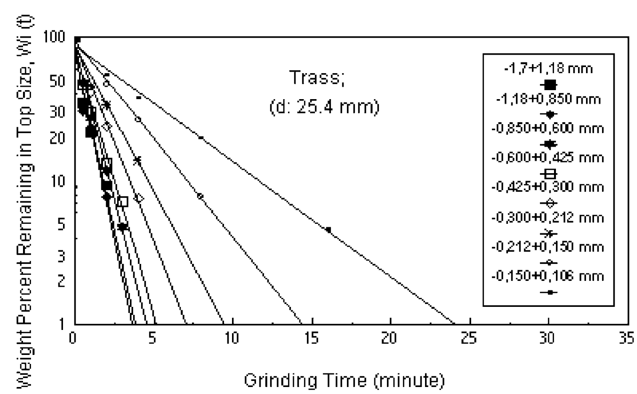

Fig. 7. First-order plots for 25.4-mm ball diameter of trass.

on the properties of the material and the grinding conditions.

3. Materials

Limestone, trass and clinker samples taken from Göltaş cement factory (Isparta/Turkey) were used as the experi-

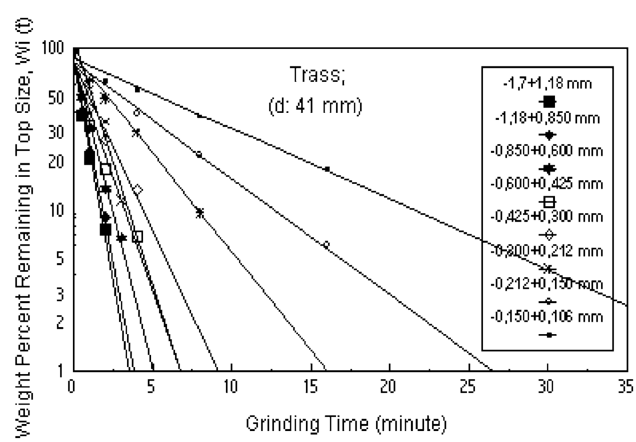

Fig. 8. First-order plots for 41-mm ball diameter of trass.

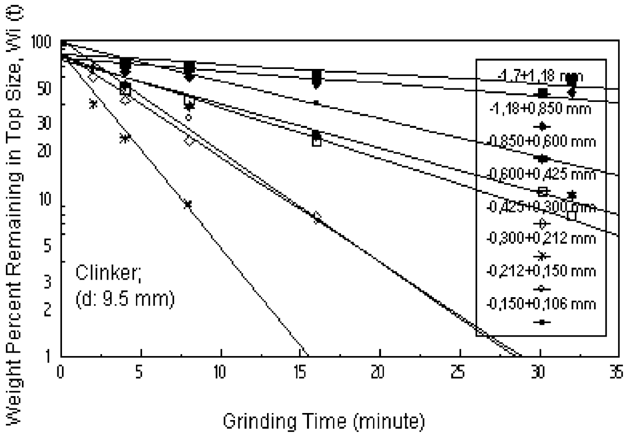

Fig. 9. First-order plots for 9.5-mm ball diameter of clinker.

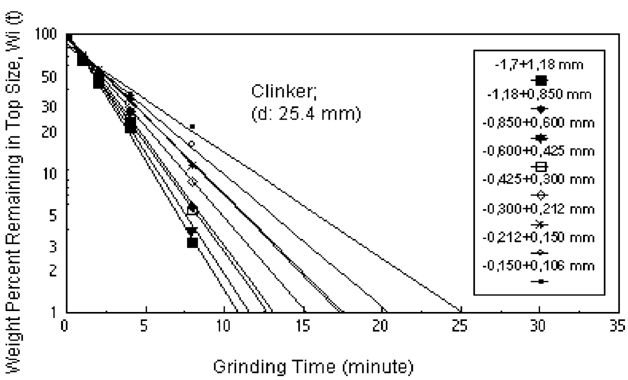

Fig. 10. First-order plots for 25.4-mm ball diameter of clinker.

mental materials. The chemical properties of the limestone, trass and clinker samples are presented in Table 1.

4. Grinding tests

Firstly, Standard Bond Work Index tests were made for limestone, trass and clinker samples. The Bond Work Index

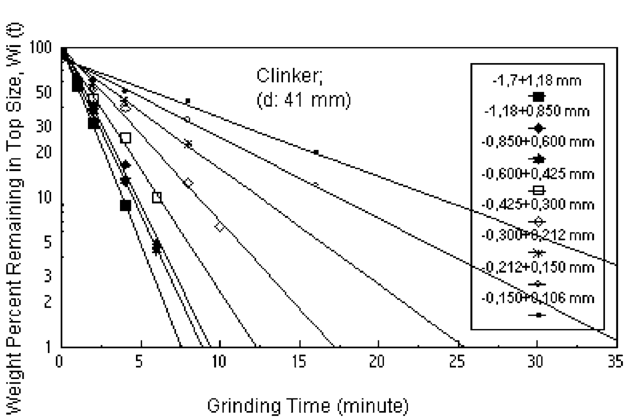

Fig. 11. First-order plots for 41-mm ball diameter of clinker.

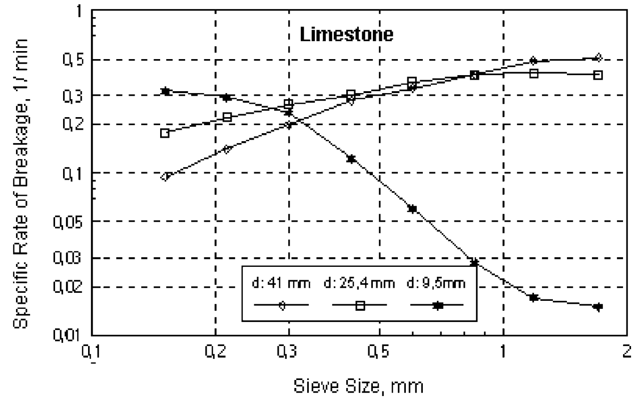

Fig. 12. Specific rates of breakage for limestone.

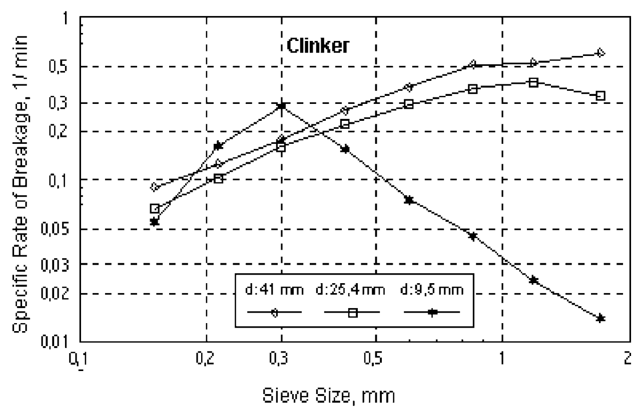

Fig. 13. Specific rates of breakage for clinker.

values of limestone, trass and clinker samples were determined as 13.52, 7.85 and 13.69 kW h/ton, respectively. The standard set of grinding conditions used is shown in Table 2, for a laboratory mill of 6280 cm^3 volume. Eight monosize fractions ($-1.7+1.18$, $-1.18+0.850$, $-0.850+0.600$,

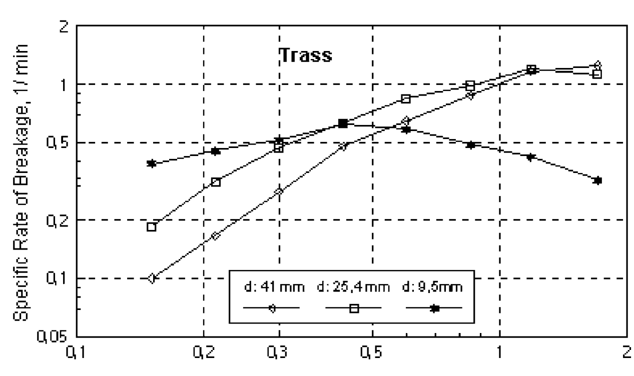

Fig. 14. Specific rates of breakage for trass.

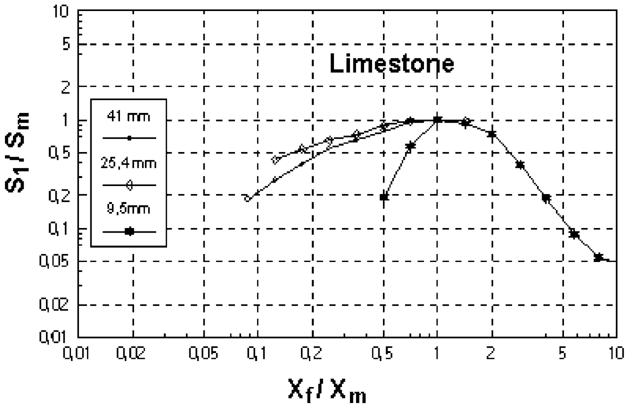

Fig. 15. Variation of specific rate of breakage with nondimensional feed size for limestone.

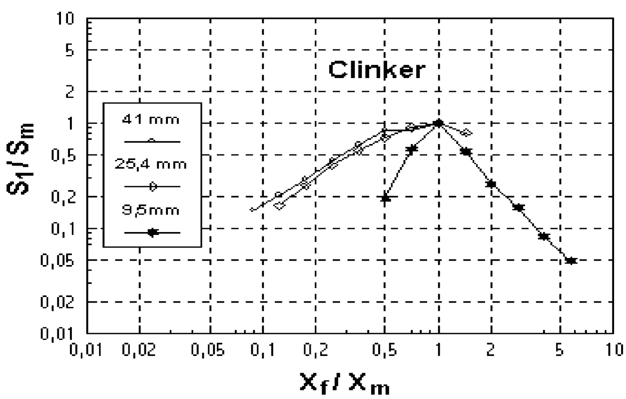

Fig. 16. Variation of specific rate of breakage with nondimensional feed size for clinker.

$-0.600+0.425$, $-0.425+0.300$, $-0.300+0.212$, $-0.212+0.150$ and $-0.150+0.106$ mm) were prepared and ground batch wise in a laboratory-scale ball mill for determination of the specific rate of breakage. Each sample was taken out of the mill and dry-sieved for product size analysis.

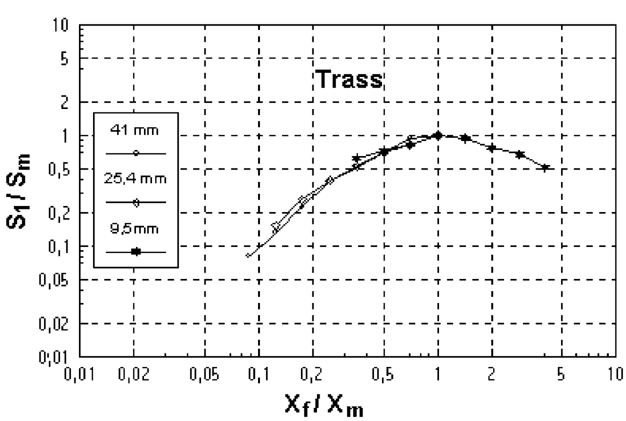

Fig. 17. Variation of specific rate of breakage with nondimensional feed size for trass.

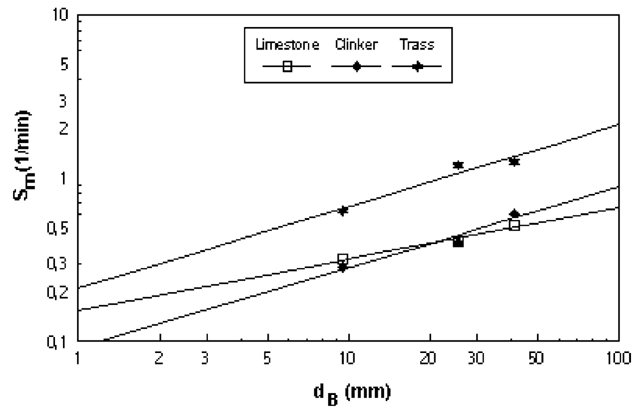

Fig. 18. Correlation of maximum value of specific rate of breakage with ball diameter.

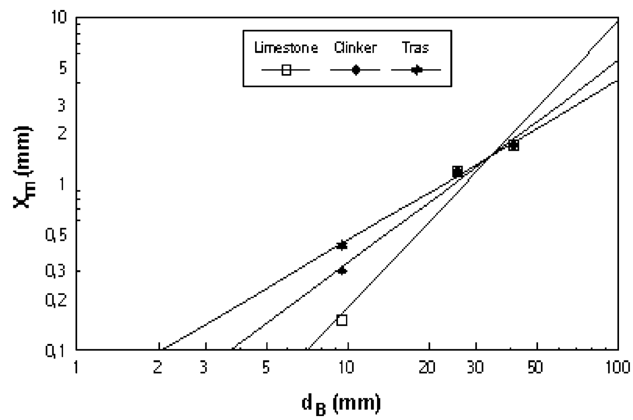

Fig. 19. Correlation of optimum feed size with ball diameter.

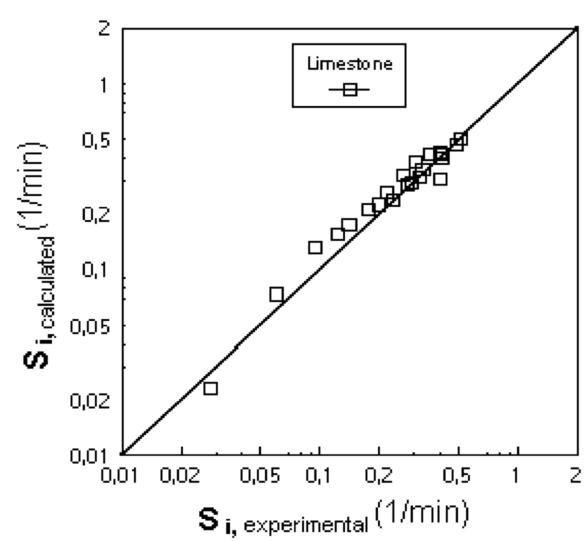

Fig. 20. Comparison of experimental value and calculated value for limestone.

5. Results and discussions

The first-order plots for the various feed sizes of limestone, trass and clinker samples are given in Figs. 3–11. The results indicated that breakage generally followed a first-order relation and values of S_i could be determined. Additionally, Figs. 12–14 show the values of S_i for grinding of the three-ball size studied, as a function of size.

Austin et al. used Eq. (3) to express the change of S_1 with the feed size. This formula can explain experimental values in the fine particle size range, but not in the coarse particle size range. Snow (1973) [7] showed that relationship between S_1 and feed size was empirically described by Eq. (4).

$$\frac{S_1}{S_m} = \left(\frac{X_f}{X_m}\right)^{\alpha} \exp\left(-\frac{X_f}{X_m}\right) \tag{4}$$

where X_m is the feed size at which S_1 is the maximum, i.e., S_m.

It was shown that the variation of the nondimensional specific rate of breakage with feed size of materials could be approximately expressed by Eq. (4), as proposed by Snow (1973) [7], but correspondence between the calculated and experimental results was not perfect. Then, Kotake et al. [6] revised the exponential function term in Snow's Eq. (5) and obtained the following:

$$\frac{S_1}{S_m} = \left(\frac{X_f}{X_m}\right)^{\alpha} \exp\left(-c\frac{X_f - X_m}{X_m}\right) \tag{5}$$

This suggests that the basis of the size reduction in a ball mill results from the interactions between grinding balls and particles, and that the essence of this mechanism does not change even if feed materials are changed. Eq. (5) can explain the experimental results well and gave value for the constant $c=1$ for each sample and $\alpha=1.01$ for limestone, $\alpha=1.33$ for trass and $\alpha=1.01$ for limestone from the fitted curve.

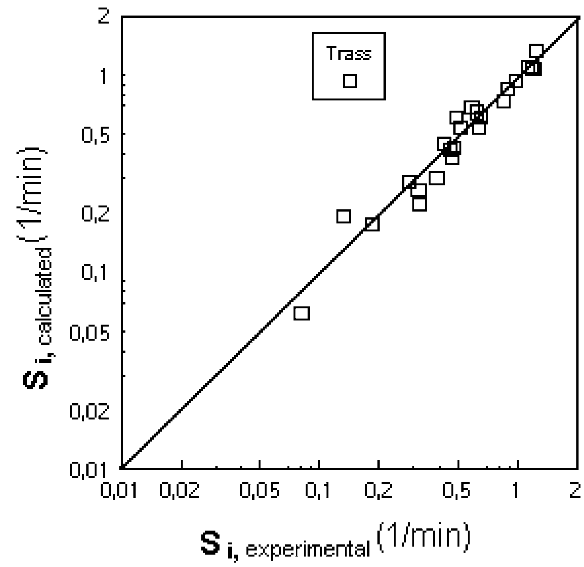

Fig. 22. Comparison of experimental value and calculated value for trass.

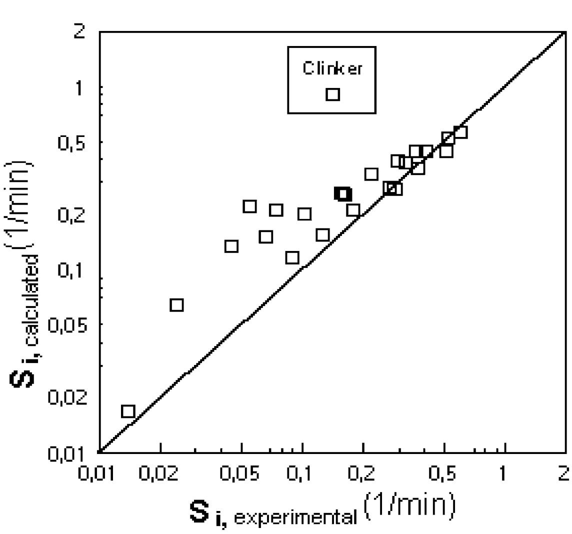

Fig. 21. Comparison of experimental value and calculated value for clinker.

Figs. 15–17 show the relationship between the optimum feed size and the ball diameter for limestone, trass and clinker. The relationship is similar for grinding with ball media mills. In these experiments, Eqs. (6)–(8) were obtained for limestone, clinker and trass, respectively. Fig. 18 shows the relationship between the maximum value of the specific rate of breakage and ball diameter (d_B) of the cement materials. Eqs. (9)–(11) were obtained for solid lines shown in Fig. 19.

$$X_m = 0.0034 d_B^{1.725} \quad \text{(limestone)} \tag{6}$$

$$X_m = 0.020 d_B^{1.217} \quad \text{(clinker)} \tag{7}$$

$$X_m = 0.050 d_B^{0.962} \quad \text{(trass)} \tag{8}$$

$$S_m = 0.155 d_B^{0.313} \quad \text{(limestone)} \tag{9}$$

$$S_m = 0.091 d_B^{0.493} \quad \text{(clinker)} \tag{10}$$

$$S_m = 0.212 d_B^{0.499} \quad \text{(trass)} \tag{11}$$

Substituting Eqs. (6) and (9), Eqs. (7) and (10), and Eqs. (8) and (11) into Eq. (5), the specific rate of breakage for each cement material can be expressed by the feed size and the ball diameter.

$$S_1 = C_1 d_B^m X_f^{\alpha} \left(-C_2 \frac{X_f}{d_B^n}\right) \tag{12}$$

where C_1, C_2, m and n are constants, respectively. The values for constants C_1, C_2, m, n and α in Eq. (12) were summarized in Table 3.

The experimental values and the calculated results obtained by Eq. (12) were compared in Figs. 20–22. Eq. (12) mostly satisfies the experimental values in a wide range of feed size, and Eq. (12) is useful especially when evaluating the specific rate of breakage in the actual operation.

6. Conclusions

In this study, batch grinding tests of cement materials (limestone, trass and clinker) with a ball mill were carried out. The effects of feed size and ball diameter on the specific rate of breakage (selection function) were investigated.

The variation of the nondimensional specific rate of breakage with feed size was roughly analogous, and it was independent of ball diameters and kind of materials.

It can be seen that there is a little divergence between the experimental and calculated values for the clinker, because clinker is formed as an artificial sample.

The relationships between the optimum feed size and the ball diameter were deduced. The relationships between the maximum specific rate of breakage and the ball diameter for the materials were also determined.

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