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The specific selection function effect on clinker grinding efficiency in a dry batch ball mill

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Abstract

Dry grinding experiments on cement clinker were carried out using a laboratory batch ball mill equipped with a torque measurement. The influence of the ball size distribution on the specific selection function can be approached by laboratory runs using mono-size balls. The breakage is more efficient with maximal specific selection functions at the initial size reduction stage. But, in terms of cement finish grinding all stages of grinding are determinant for the production of a required Blaine surface area (3500 cm^2/g). So, the choice of ball size according to a maximal specific selection function leads to an increase of the energy consumption. In addition, investigations on the mono-sized fractions and on the crude material (size minus 2.8 mm) demonstrate that the energy efficiency factor can be optimized using ball size corresponding to relatively low specific selection function.

Keys words

Cement clinker, Ball mill, Dry grinding, Specific energy, Specific selection function, Blaine fineness, Energy efficiency.

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1. Introduction

In the cement industry, the clinker grinding step consumes about one-third of the power required to produce one ton of cement. This refers to an average specific power consumption of 57 kWh per ton (Seebach and Schneider, 1986) and specific carbon dioxide emissions intensity for electricity generation of 9.1kg CO_2 per ton (Worrel et al, 2000). Considering these factors, a small gain in comminution efficiency can have not only a large impact on the operating cost of a plant, but also a reduction in greenhouse gas emission. Several investigators have presented convincing cases for the use of population balance models as an alternative to the Bond energy-size reduction equation for scale-up design (Herbst and Fuerstenau, 1980; Austin et al., 1984). The breakage process is characterized by two basic functions: a selection function that represents the fractional rate of breakage of particles in each size class; and a breakage function that gives the average size distribution of daughter fragments resulting from primary breakage event. 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 in ball milling. It is however known that there is a specific ball size which maximises the breakage rate of a given size fraction of a material (Austin et al, 1984; Gupta et al, 1985). Thus, a number of empirical relations have been proposed between the maximum specific rate of breakage and the ball diameter for the cement clinker (Deniz, 2003) and other solid materials (Kotake, 2002). However, finish grinding circuits in the cement industry are operated to produce a powder of 3500 cm^2/g Blaine surface area, taken as an index of the cement quality, and no attempt is made to produce a specified size distribution (Opoczky, 1977). So, the specific energy demand of this grinding process cannot be evaluated only by the size reduction analysis. The objective of the present study was to analyse the effect of the specific selection function, obtained from the

grinding tests, which reflects the size reduction energy efficiency (Herbst and Lo, 1989), on the energy consumed to produce a desired Blaine surface area. In particular, we aim to correlate the specific selection functions, with the energy efficiency factor, defined by the production of 3500 cm^2/g surface area per unit of specific grinding energy.

2. Background

Considering a mass of material *M* in a ball mill to be divided into n narrow size intervals with maximum size x_1 and minimum size x_{n+1}, the ith size interval, bounded by x_1 above and x_{i+1} below, contains a mass fraction of material $m_i\ (t)$ at time *t*. When breakage is occurring in an efficient manner, the breakage of a given size fraction of material usually follows a first-order law. Since the mill hold up, *M,* is constant, this becomes:

$$\frac{dm_i(t)}{dt} = -S_i\, m_i(t) \tag{1}$$

Where S_i is proportionality constant and it is called the selection function for the ith size interval that denotes the fractional rate at which material is broken out of the ith size interval. Under conditions where grinding kinetics are directly proportional to the specific power input (net) to the mill (*P/M*), Herbst and Fuerstenau (1973) showed that the first order disappearance kinetic equation in the energy normalized form can be expressed by:

$$\frac{dm_i(E)}{dE} = -S_i^E m_i(E) \tag{2}$$

where *E* is the specific energy equal to the product of specific power by grinding time *t*. In equation (2), the specific selection function S_i^E is dependent of ball size (Lo and Herbst, 1986; Touil et al., 2003) and usually independent of mill design and operating conditions (Herbst and Fuerstenau, 1973; Malghan and Fuerstenau, 1976). It is extremely useful for computational simplification involved in tumbling mill simulation since the evolution of size

distribution, resulting from size reduction stage, depends only on the ball size and the energy expended during the grinding step.

From the requirements for optimum quality and strength, the fineness of the cement is usually expressed not as size distribution but by a specific surface area of 3200-3500 cm^2/g (Ito, 2000). Clinker grinding process are often monitored and controlled by measuring the product surface area using a simple air-permeability procedure such as the Blaine test.

3. Experimental material and method

The stainless steel mill used in the experiments was 17.15 cm in diameter and 20.05 cm in length with four lifters bars (0.8 cm in height). This mill was driven directly by Leroy-Somer variable speed drive (0.75 kW motor, 0 to 100 rpm output) coupled with a HBM torque transducer (0 to 20Nm) and a scout 55 amplifier connected with a computer to accurately measure the torque drawn by the mill at the shaft. To obtain the net torque drawn by the tumbling balls, the torque of the empty mill (which represent bearings losses, etc.) must be deducted from the gross torque readings. The ball load (9.5 kg) filled the mill to 45% of its volume. The feed charge was held constant at 874 g, which occupied 80% of the void space between the balls at rest. For all experiments, the mill was rotated at 65 rpm (60% of the critical speed). These conditions were selected because the net mill power draw under these operating variables is maximal (Touil et al., 2004). Different mono-sized fractions between 4 and 0.075 mm of cement clinker obtained from Lafarge Martres plant (France) were prepared using a $\sqrt{2}$ sieve series to be used as the feed charge. To obtain the specific selection function and the Blaine specific surface of this material, each monosized fraction was individually ground in dry conditions at different specific energy, using different ball diameters (10, 20 and 30 mm). The other operating conditions were kept constant at those mentioned above. The particle size distributions of the samples were determined by dry sieving technique. It

was observed that the power input to the mill slightly decreased when the material becomes very fine.

4. Results and discussion

4.1 Specific selction function of ball size distribution

Estimated values of the specific selection function for each feed size interval are plotted versus particle size for different ball diameters in Fig.1. Similar trends with respect to the variation of the selection function S_i versus ball size were reported by (Austin et al., 1984). The optimum values obtained for 10, 20 and 30 mm ball diameter are about 0.45, 0.83 and 1.8 mm. The optimum feed sizes calculated according to the relationships proposed by (Deniz, 2003) have about the same values. Fig. 2 shows the variation of S_i^E versus the ball size for two specific feed size intervals. The results can be fitted by linear equations. The specific selection functions for (1– 1.4mm) and (0.25 – 0.18 mm) feed size intervals obtained from composite grinding balls of an average ball diameter of 24.5mm can be calculated by:

$$\overline{S_i^E} = \sum_{\ell=1}^{k} S_{i,\ell}^E \, . \, y_\ell \tag{3}$$

y_l is the weight fraction of balls of size l and k the number of different ball sizes.

This result verifies the validity of the expression proposed previously by Austin et al. (1976), assuming the absence of any interaction between the balls for the calculation of the average selection function $\overline{S_i}$. Therefore, the influence of ball size distribution on specific selection function can be approached by laboratory tests using single size balls in the mill. For this purpose, Lo and Herbst (1986) have suggested investigations with ball size distribution often used in laboratory tests for scale-up design.

4.2 Size distribution of comminuted particles

Using the 20 mm ball diameter, the experimental size distributions produced at 1.30 kWh/t specific energy for the (2– 1.4 mm) and (1–0.71 mm) feed size intervals are reported on Fig. 3 It can be seen that more fines are produced grinding particles in the (1– 0.71 mm) size interval rather than in the (2–1.4 mm) size range. For example, the cumulative fraction passing 0.075 mm obtained is 11 % for the (1–0.71 mm) feed size, while it is 8% for the (2–1.4 mm) material size. Another example is given in Fig.4 which is based on data for the (2–1.4 mm) feed size interval ground with different ball diameters. It is shown also that for low specific energy (0.32 kWh/t) at the beginning of the grinding, the cumulative fractions passing 0.075 mm obtained is greater with 30 than the 20 and 10 mm balls. Referring to Fig. 1, it can be seen that S_i^E for 20 and 30 mm balls has a nearly maximal values for the (1-0.71 mm) and (2-1.4 mm) size range. We can conclude that, in terms of energy efficiency, the breakage with a maximal specific selection function is significantly greater in the initial stages of grinding corresponding to size reduction process.

4.3 Blaine fineness and specific energy consumption

The evolution of the Blaine specific surface area of the (1-0.71mm) cement clinker fraction versus the specific energy is shown in Fig. 5. The Blaine specific surface increases with the specific energy. At a fineness of 3500 cm^2/g, the specific energy is 40 kWh/t using 20 mm size balls. The created specific surface is influenced by the ball size. The curves diverge at different initial specific breakage rate. For a given specific energy consumption, the Blaine specific surface and the energy efficiency are greater with the 10 mm balls than with the 20 mm balls. Now, it is shown that a specific selection function of 0.48 $(kWh/t)^{-1}$ using 10mm size balls (see Fig.1) leads to higher energy efficiency than 0.9 $(kWh/t)^{-1}$ with 20 mm balls. Using 20mm ball diameter, Fig.6 shows also that the grinding of the (4-2.8mm) feed size interval with a low specific selection function of 0.35 $(kWh/t)^{-1}$ (extrapoled value in the

coarse region, Fig.1) leads to a higher energy efficiency than 0.9 $(kWh/t)^{-1}$ for the (1-0.71mm) size range. Therefore, all stages of the grinding process are determinant with respect to the total specific energy expended to produce a desired Blaine fineness. So, the choice of a specific ball size which maximises the specific selection function of a given size fraction doesn't remain an accurate measure of the energy efficiency of cement clinker grinding.

Fig. 7 presents the evolution of the production of surface area per unit grinding energy (cm^2/J), which is an indicator of the energy utilization, versus the specific energy. The cement clinker fraction (2-1.4 mm) is taken here as an example. The figure reveals that the energy utilization decreases with the energy consumption. Beyond an average specific energy of 15kWh/t, a fast decrease of the energy utilization is observed. During the first period, the consumed energy is proportional to the increase of the created surface. After this size reduction stage, the process becomes more inefficient, probably due to the increasing amount of fine powder in the mill. Indeed small particles may be more difficult to break or have a cushioning effect on the impacts of media. Consequently, the lower change of the product fineness corresponds to the higher energy loss and dissipation.

4.4 Energy efficiency factor optimisation

In order to optimize the cement clinker grinding operation, the energy efficiency factor (η), defined by the production of 3500 cm^2/g specific surface area per unit of specific energy consumed is evaluated for different feed particle size ground with 30 mm ball diameter. Fig. 8 presents the variation of η versus the specific selection function. The energy efficiency factor η reaches a maximum value of 28 cm^2/J. The optimal is obtained for a specific selection function with about 0.55 $(kWh/t)^{-1}$. At specific selection function below the optimum, the grinding results are poor due to a low breakage process which is unable to break the particles. At higher specific selection function, the breakage process is higher

than necessary, and therefore a higher proportion of fines amount is generated. The fine particles are more subjected to agglomerative forces which can lead to slow down the grinding process and increase the amount of needed energy for creating surface. For the desired Blaine surface area, about 29% more energy is required to ground cement clinker with a maximal specific selection function of 1.0 $(kWh/t)^{-1}$ in comparison to what is needed with 0.55 $(kWh/t)^{-1}$. Artificially clinker feed sample of 0.30 mm median particle size distribution is prepared with different mono-sized fractions (table 1) and ground using different ball load distribution composed of grinding balls. This condition is commonly applied in practice. Fig. 9 presents the evolution of the energy efficiency factor versus the average ball size, which gives nearly the same grind results as a mix of ball sizes (Austin et al., 1984). It is clear that the energy efficiency factor is sensitive to the average ball size. The maximum energy efficiency factor of 39 cm^2/J is obtained with an optimal average ball size of 22 mm. Referring to Fig.1 the specific selection function of the smaller size of 0.30 mm (d_{50} is compared to the mill feed size distribution) is higher for smaller ball diameters and reaches a maximum value (calculated by the maximum breakage rate relationships) with about 9 mm ball size. Therefore, the grinding with average ball size below 22 mm corresponds to a higher specific selection function which can lead to slow down the grinding process. On the other hand, the ball size larger than 22 mm corresponds to a lower specific selection function which is not able to break successfully the particles. So, it is concluded again for this artificially clinker feed size distribution that the energy efficiency factor can be optimized using average ball size corresponding to relatively low specific selection function.

5. Conclusions

Batch dry grinding tests of cement clinker were performed in a ball mill measuring the power input. The effect of ball size distribution on specific selection functions was investigated. At the initial size reduction stage the experimental results shown that the breakage process is

more efficient with a maximal specific selection function. The specific energy consumed for creating surface is affected by the fine material environment in the grinding chamber. All stages of grinding are determinant for the production of 3500 cm^2/g Blaine surface area. Therefore, conditions ensuring an initial maximal specific selection function lead to an increase of the energy consumption. This study demonstrates that the energy efficiency can be optimized using ball size as an operating variable corresponding to relatively low specific selection function.

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Nomenclature

E	Specific energy input to mill
i	Integer denoting √2 size interval
m_i	Mass fraction of material in the size interval i
M	Mass of material in the mill
P	Net power drawn by the mill
S_i	Size discretized selection function
S_i^E	Specific selection function for ith size interval
$\overline{S_i}$	Average discretized selection function
$\overline{S_i^E}$	Average specific selection function for ith size interval
t	Time
x_i	Particle size
y_l	Weight fraction of balls of size l
η	Energy efficiency factor

Fig.1. Specific selection function versus particle size for various ball sizes

Fig.2. Variation of specific selection function versus ball size

Fig.3 Experimental product size distributions for the (2 -1.4 mm) and (1-0.71 mm) initial size ground using the 20 mm size ball

Fig.4. Experimental product size distributions for the (2- 1.4 mm) initial size ground using 10, 20 and 30 mm size balls

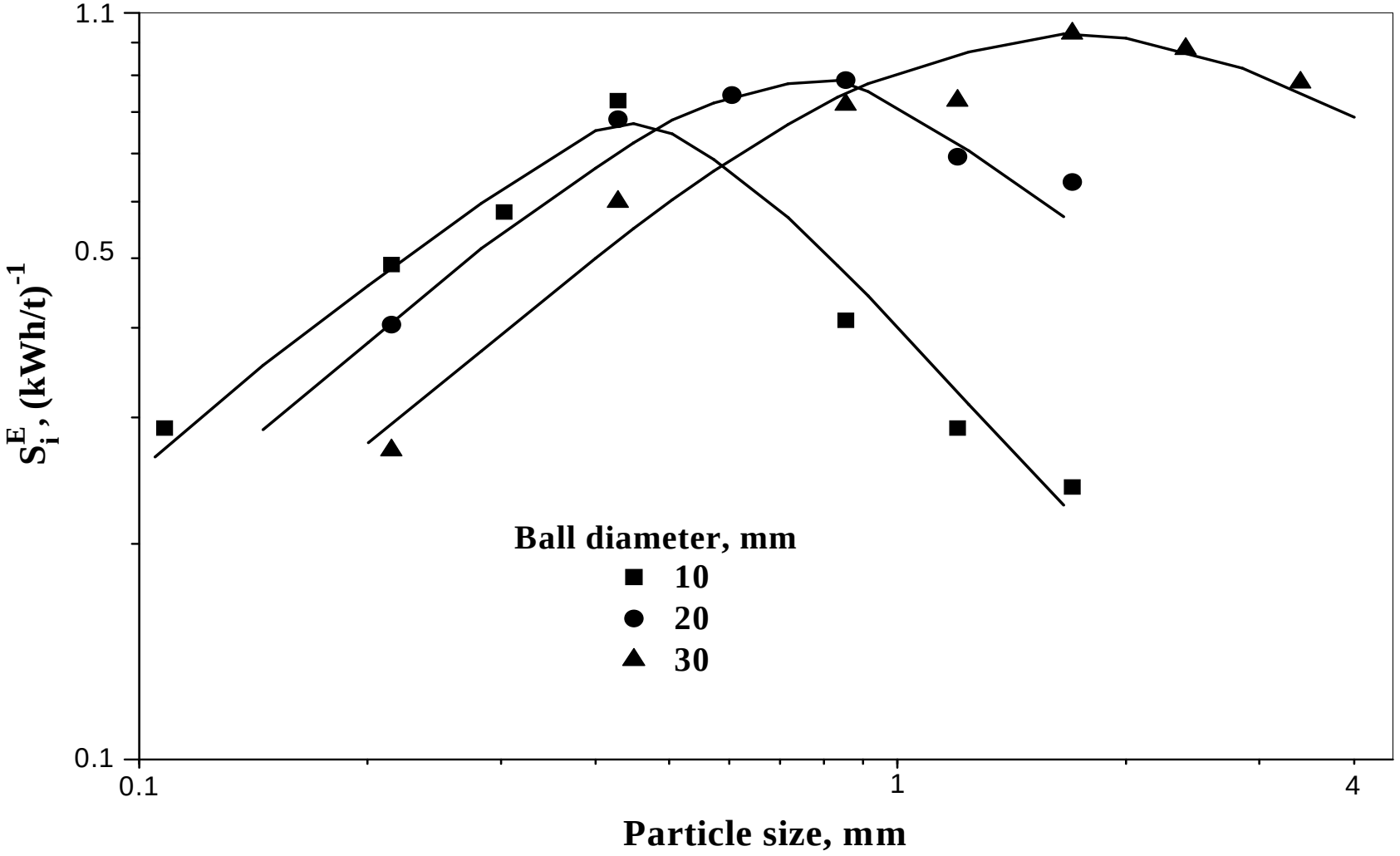
Fig.5. Blaine specific surface versus specific energy with the 10 and the 20 mm size balls

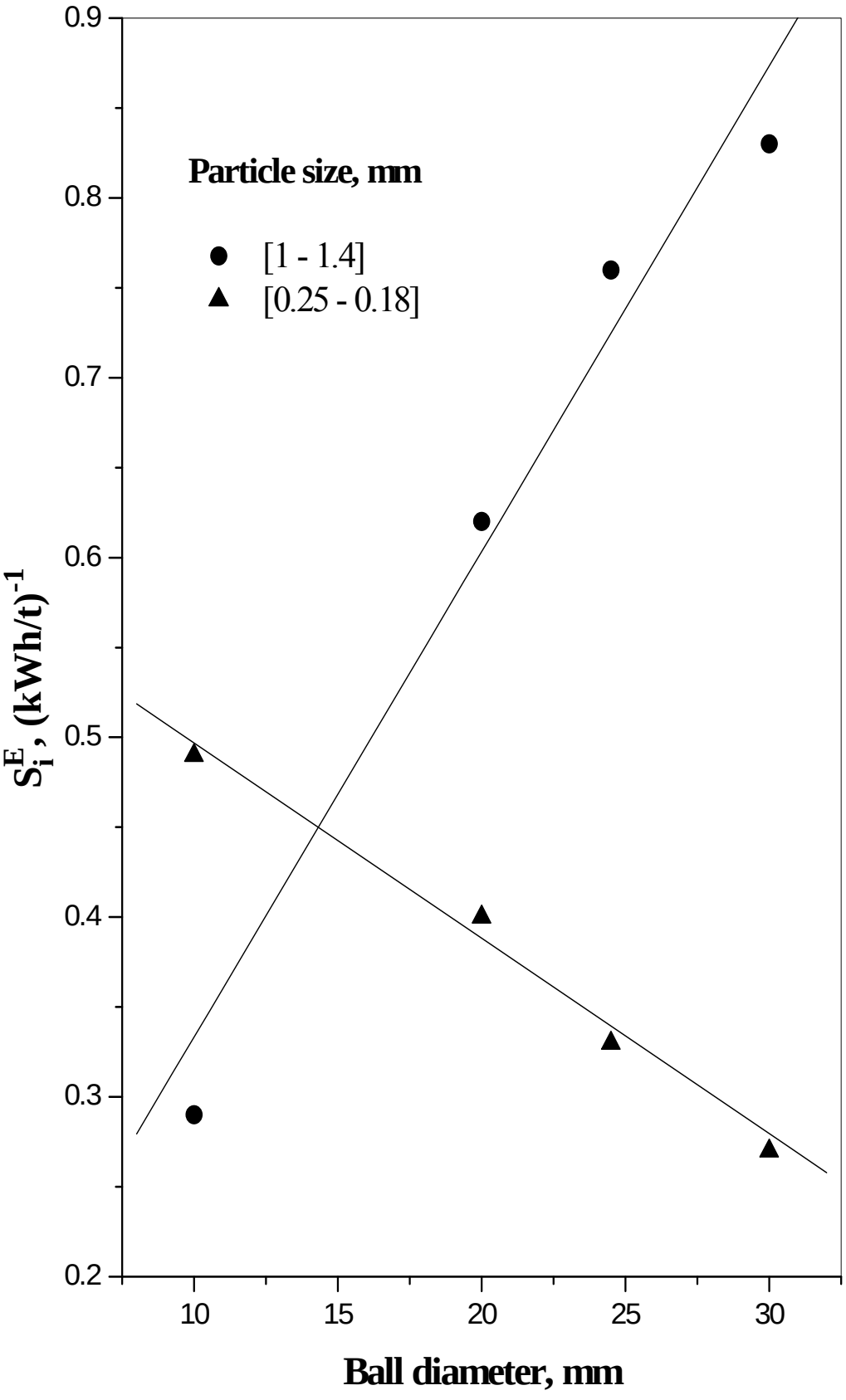
Fig.6 Blaine specific surface versus specific energy for the (4 -2.8 mm) and (1-0.71 mm) initial size ground using the 20 mm size ball

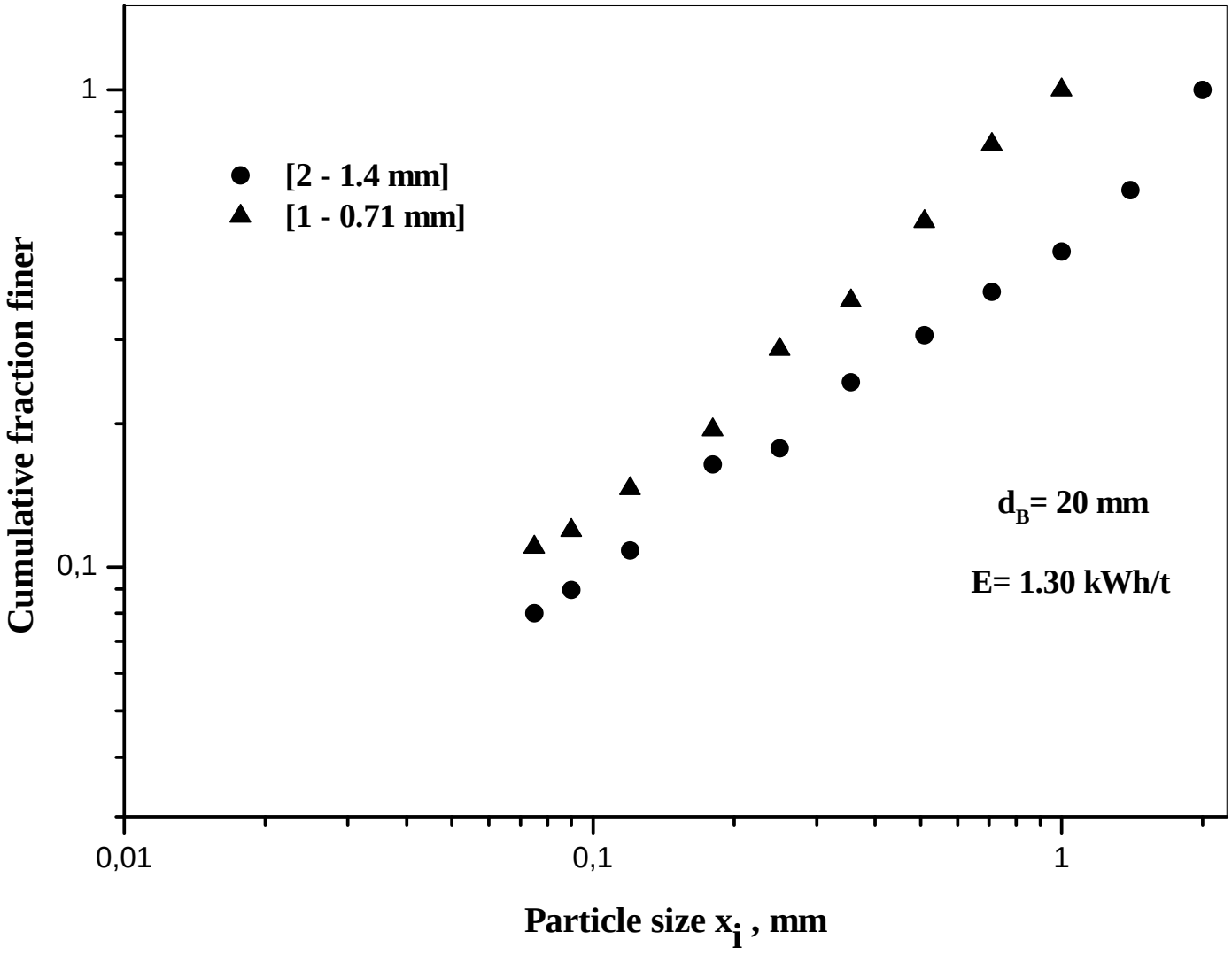
Fig.7. Energy utilization versus specific energy

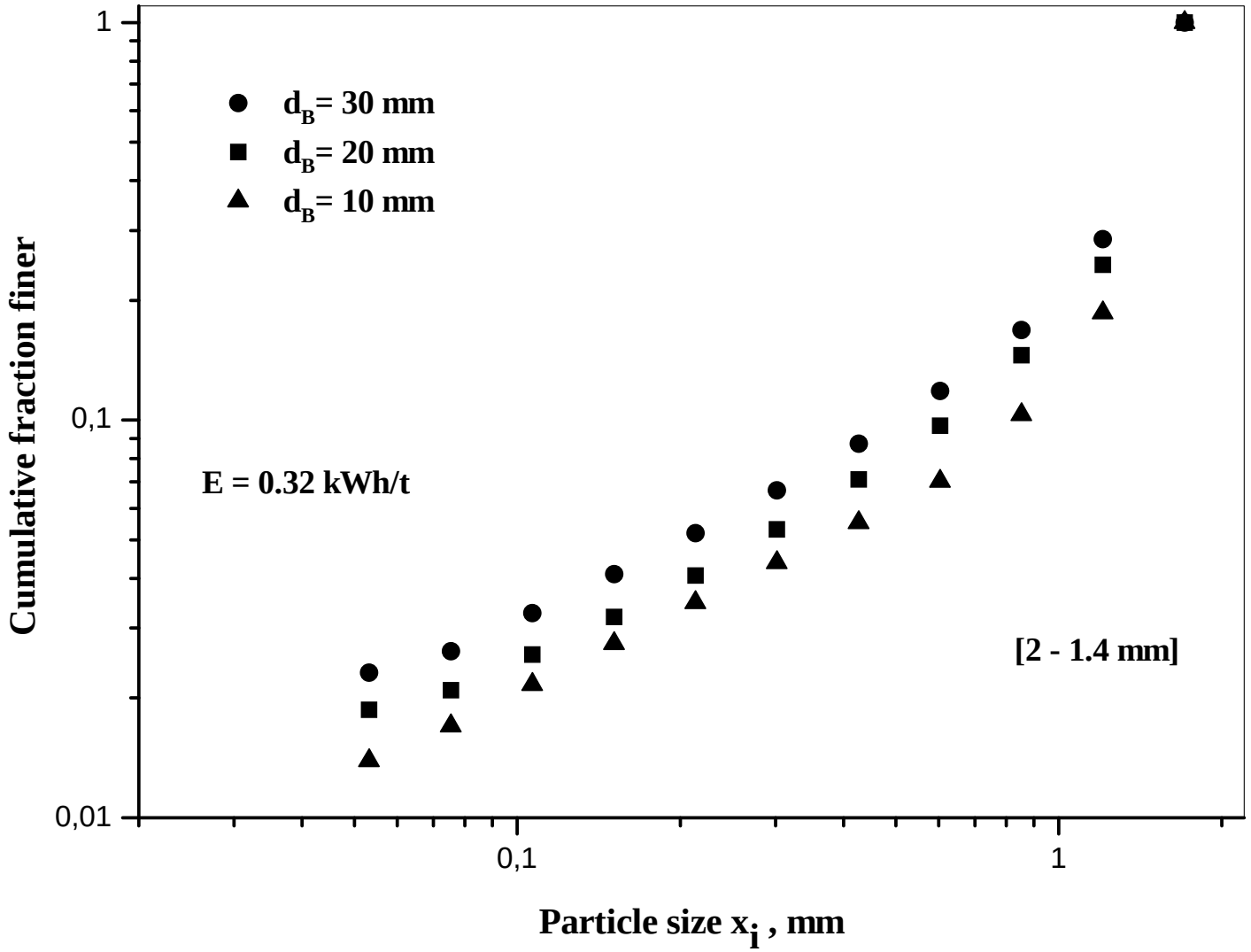
Fig.8. Variation of the energy efficiency factor versus the specific selection function

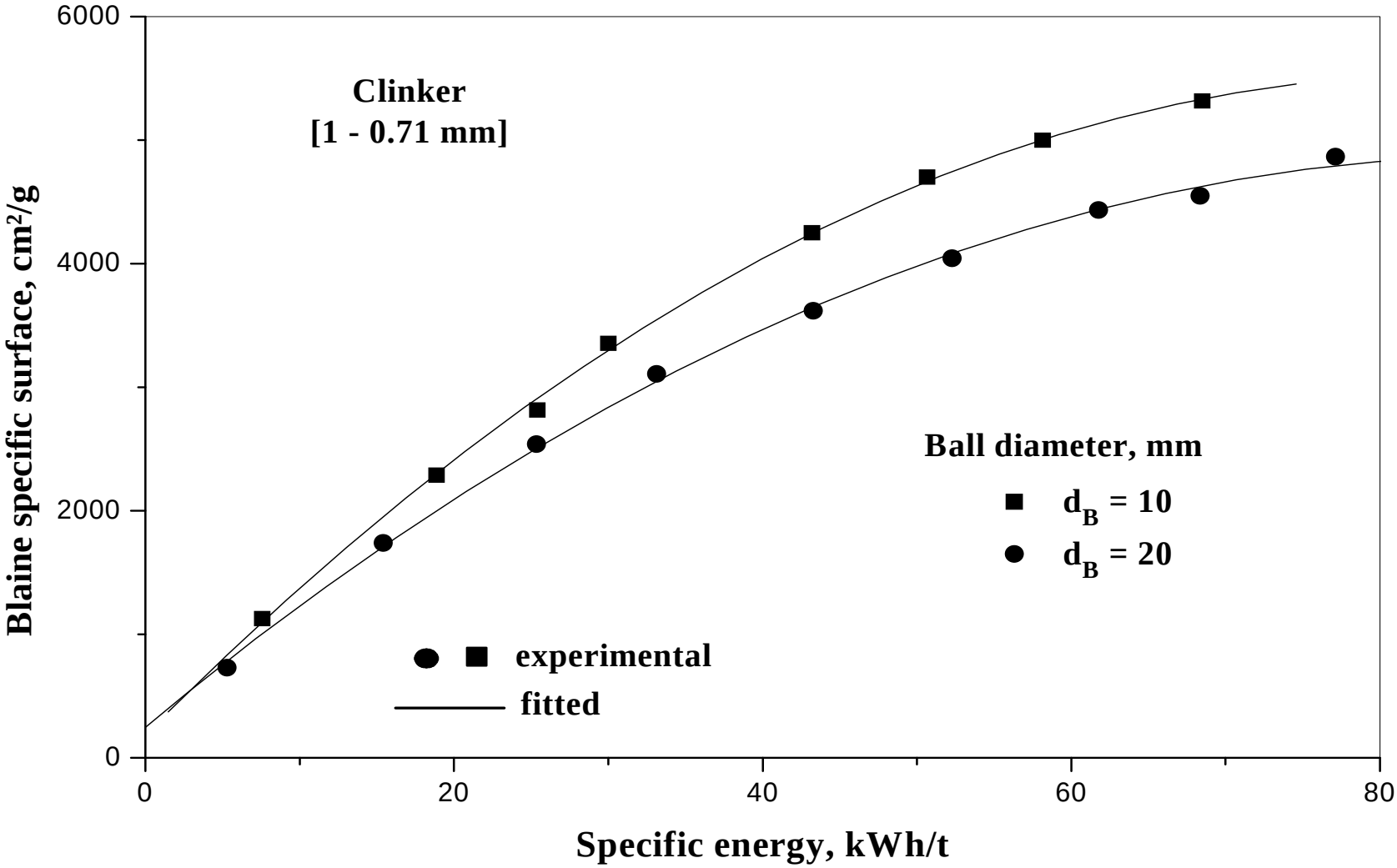
Fig.9. Variation of the energy efficiency factor versus the average ball size

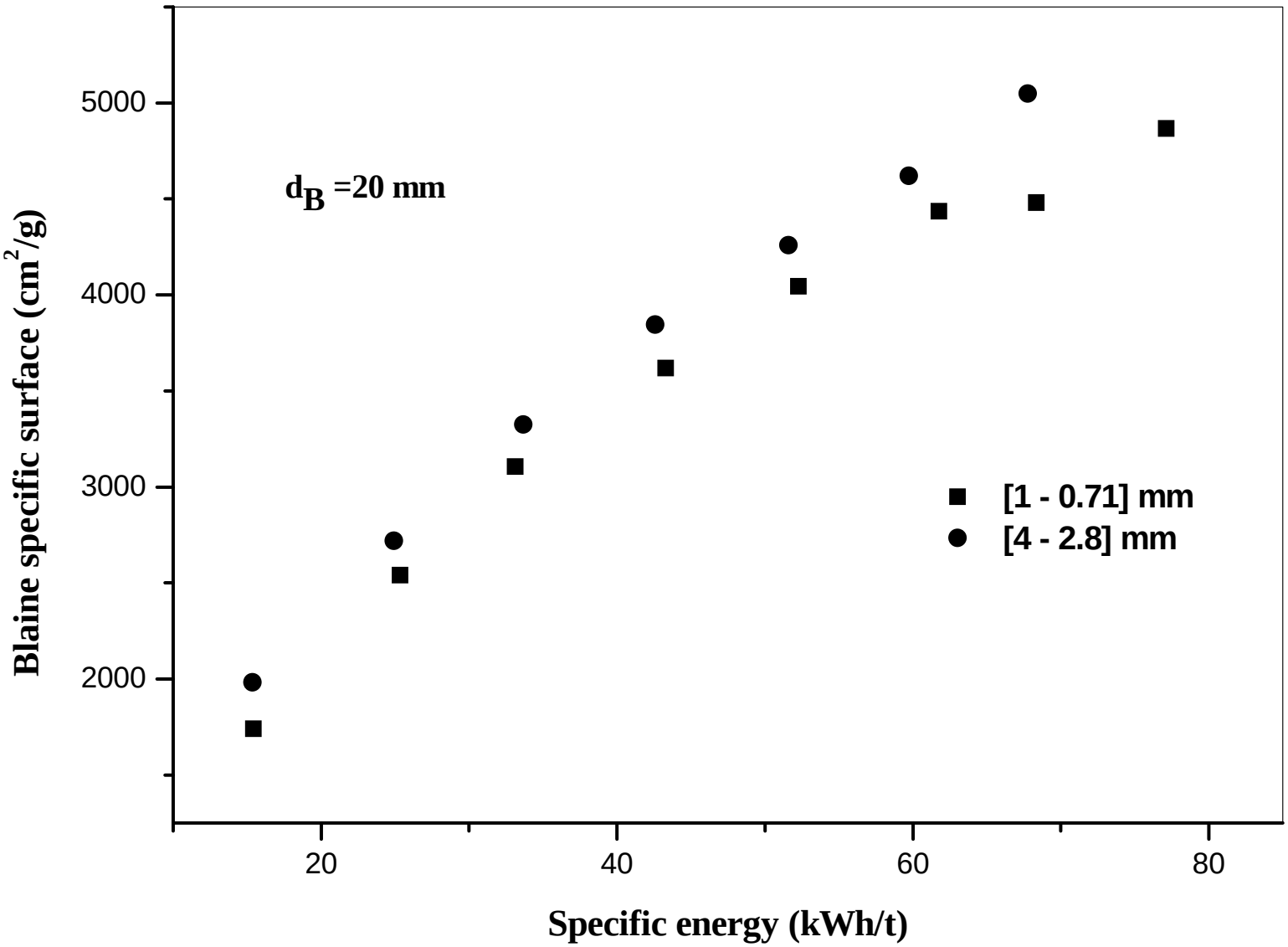

1.1
0.5
0.1
0.1
1
4
S_i^E, (kWh/t)$^{-1}$
Particle size, mm
Ball diameter, mm
10
20
30

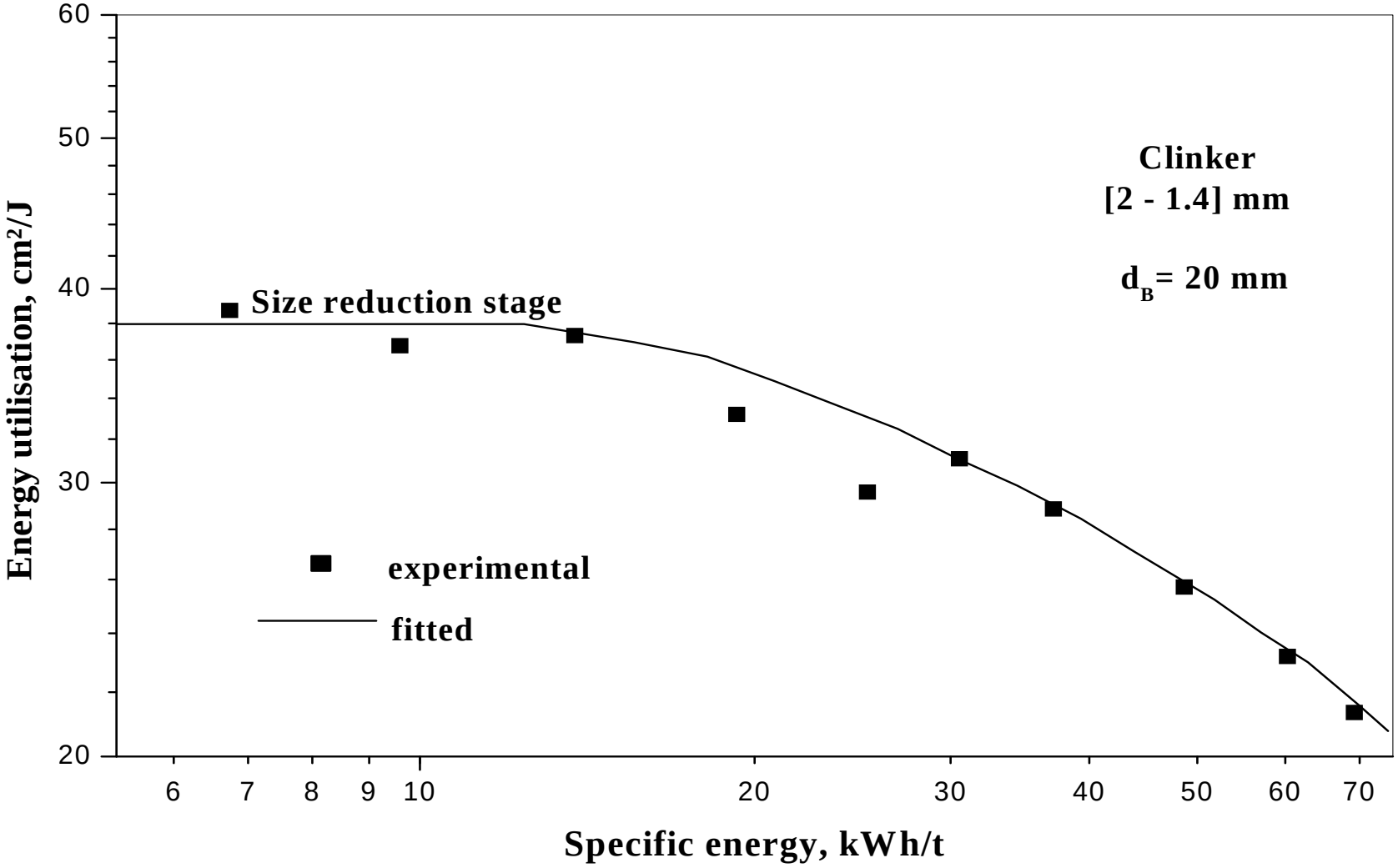

Particle size, mm
[1 - 1.4]
[0.25 - 0.18]
S_i^E, (kWh/t)$^{-1}$
Ball diameter, mm
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
10
15
20
25
30

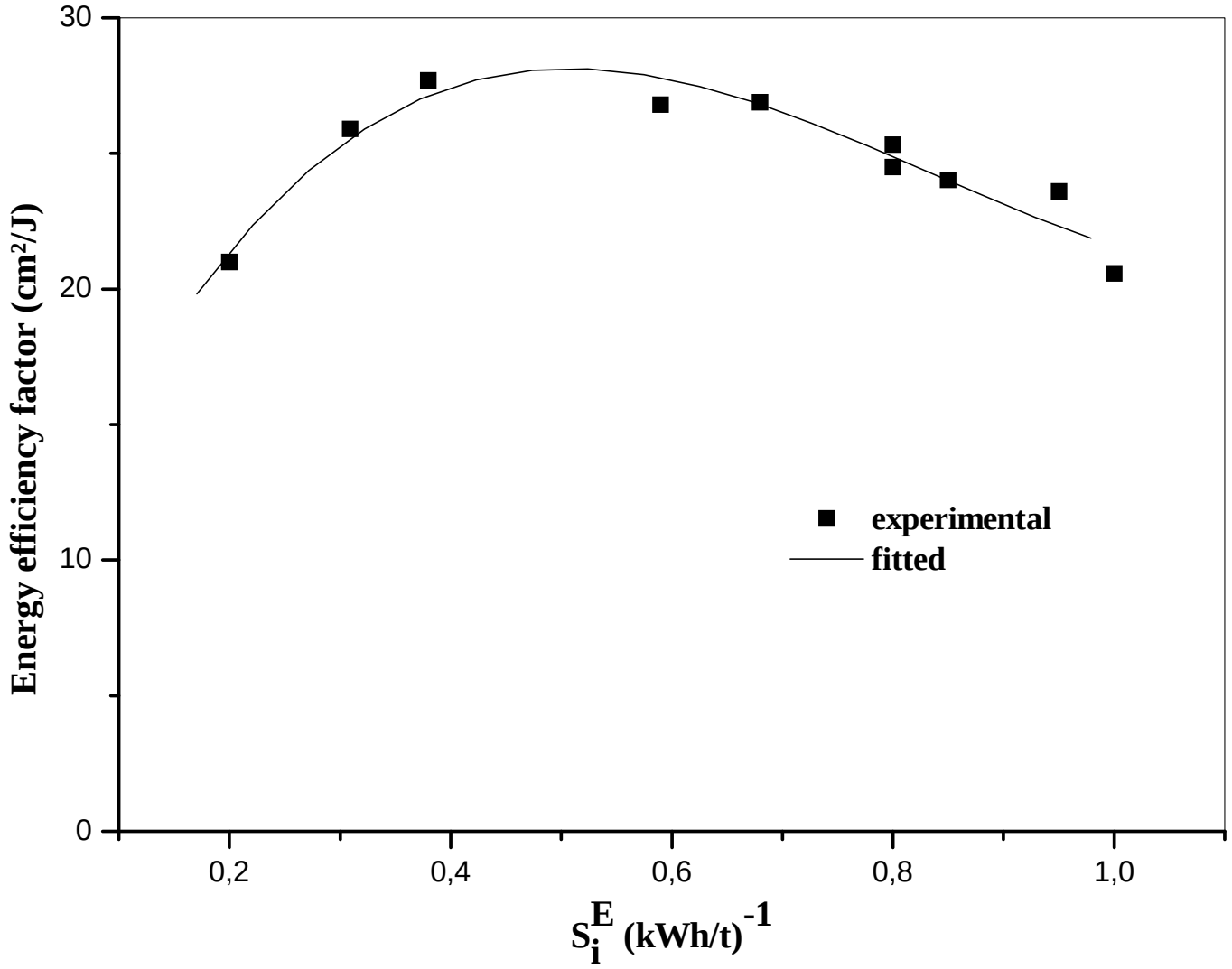

Cumulative fraction finer
1
0,1
0,01
0,1
1
[2 - 1.4 mm]
[1 - 0.71 mm]
d_B= 20 mm
E= 1.30 kWh/t
Particle size x_i , mm


1
0,1
0,01
0,1
1
Cumulative fraction finer
Particle size x_i , mm
d_B= 30 mm
d_B= 20 mm
d_B= 10 mm
E = 0.32 kWh/t
[2 - 1.4 mm]


Clinker
[1 - 0.71 mm]
Ball diameter, mm
d_B = 10
d_B = 20
experimental
fitted
Blaine specific surface, cm²/g
Specific energy, kWh/t
0
2000
4000
6000
0
20
40
60
80


Blaine specific surface (cm²/g)
5000
4000
3000
2000
20
40
60
80
Specific energy (kWh/t)
d_B =20 mm
[1 - 0.71] mm
[4 - 2.8] mm


Energy utilisation, cm²/J
60
50
40
30
20
6
7
8
9
10
20
30
40
50
60
70
Specific energy, kWh/t
Clinker
[2 - 1.4] mm
d_B= 20 mm
Size reduction stage
experimental
fitted


30
20
10
0
0,2
0,4
0,6
0,8
1,0
Energy efficiency factor (cm²/J)
S_i^E (kWh/t)^-1
experimental
fitted

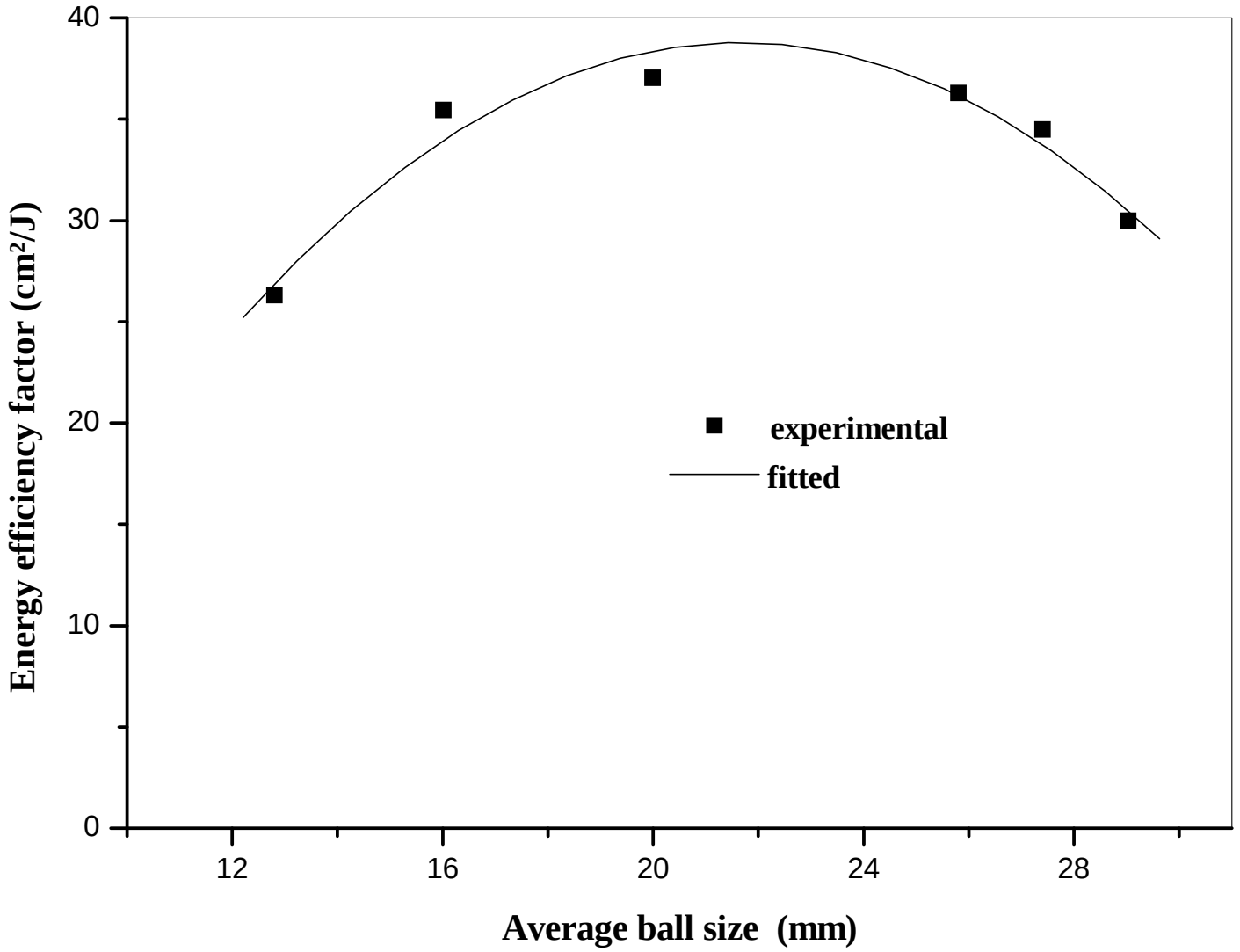

40
30
20
10
0
12
16
20
24
28
Energy efficiency factor (cm²/J)
Average ball size (mm)
experimental
fitted

Table 1. Sieve analysis of crude cement clinker

Sample N°	Aperture size (mm)	Amount retained (wt, %)
1	2.8	-
2	2	10.47
3	1.4	8.85
4	1	6.74
5	0.71	4.39
6	0.51	3.42
7	0.355	10.43
8	0.250	24.32
9	0.180	5.44
10	0.120	12.37
11	0.090	6.59
12	- 0.090	6.98
		100