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Energy efficiency of cement finish grinding 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 torque measurement. The specific energy was found to be dependent on operating parameters and clinker environment. Additional compounds such as gypsum and pozzolanic tuff improve energy efficiency. The optimal parameters allowing maximising the energy efficiency factor were determined. Energy efficiency factors were obtained both on the crude material (size minus 2.8 mm) and on a sieved fraction (1–0.71 mm). They demonstrate that a low initial rate of breakage implies higher energy efficiency. On the contrary, conditions ensuring an initial maximal rate of breakage lead to an increase of the energy consumption.

Keywords: Grinding A; Blaine surface area B; Cement D; Clinker D; Energy efficiency

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 [1]. Such large amounts of energy justify the need to improve the energy efficiency of comminution process. Any success in this direction, improving machine design and/or choosing optimal operating and environmental conditions could possibly lead to the development of new approaches toward energy saving in cement production [2]. For the three past decades, most commercial ball mill scale-up procedures have been based directly or indirectly on the empirical Bond energy-size reduction equation. A single value of the product fineness (as the 80% passing size) is usually chosen as the main variable and the energy input per unit mass of material being ground is calculated independently of operational variables and material initial size [3]. In addition, the design risk associated with this traditional scale-up method is estimated to be of the order of ±20% [4].

In recent years significant advances have been made in the development of detailed phenomenological grinding models derived from population balance considerations [4]. Therefore, the concept of specific selection function or reduced breakage rate function reflects the energy utilization or efficiency for a given mode of breakage in kinetics models as proposed by many investigators to substitute the Bond scale-up procedure in the design of grinding circuits in cement plants [4,5]. 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 [6,7].

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. In addition, the investigation only based on the particle size distribution is not satisfactory to interpret the phenomena taking place during the development of this desired fineness [8]. So, the specific energy demand of this grinding process cannot to be evaluated only by the energy size reduction stage. The objective of the present investigation is to determine the effect of different operating parameters and cement clinker composition on the energy consumed to produce a desired Blaine surface area. For this

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Table 1
Sieve analysis of crude cement clinker, gypsum and tuff

Sample no.	Aperture size (mm)	Amount retained (wt.%)		
		Cement clinker	Gypsum	Tuff
1	2.8	–	–	–
2	2	10.47	6.17	7.76
3	1.4	8.85	2.91	6.54
4	1	6.74	7.05	14.36
5	0.71	4.39	11.38	16.28
6	0.51	3.42	14.18	18.75
7	0.355	10.43	5.77	5.89
8	0.250	24.32	19.05	17.92
9	0.180	5.44	14.39	6.18
10	0.120	12.37	3.82	2.28
11	0.090	6.59	4.67	2.57
12	−0.090	6.98	10.61	1.47
		100	100	100

purpose, the energy efficiency factor defined by the production of 3500 cm^2/g surface area per unit of specific grinding energy was quantified under different conditions in a laboratory batch ball mill.

2. Experimental

2.1. Grinding equipment

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 20 Nm) and a scout 55 amplifier connected with a computer in order to accurately measure the torque drawn by the mill at the shaft.

The specific energy of grinding is the energy input into the mill related to the mass of material m_p. During the tests, the gross torque T and the rotational speed N were measured at the shaft. Considering the torque of the empty mill T_o (which represents bearings losses, etc.) and the grinding time t, the specific energy E_m can be determined by Eq. (1):

$$E_m = \frac{\int_0^t 2\pi N[T(\tau) - T_0]\mathrm{d}\tau}{m_p}. \tag{1}$$

2.2. Materials

Cement clinker and gypsum supplied by Lafarge Ciments (Toulouse, France) were used. Compact volcanic tuff (pozzolanic material) provided by Mitidja Cement Company (Algiers, Algeria) was also used for some experiments. The specific gravity of cement clinker, gypsum and tuff are respectively 3.15, 2.73 and 2.65. The initial charge of cement clinker was dried at 105 °C and sieved between 2.8 and 0.09 mm, using a $\sqrt{2}$ sieve series to obtain different cement clinker fractions. Cement clinker loads used in the experiments were either crude feed material (−2.8 mm) or mono-sized fractions (2–1.4 or 1–0.71 mm), or mixtures of the crude material with different mass fractions of the top size product (2.8–2 mm). The gypsum and tuff materials were respectively dried at 55 and 105 °C, and screened through a 2.8 mm sieve. The passing size material was collected to obtain a sufficient quantity of material in order to perform all the grinding runs with the same product. The size analysis of cement clinker, gypsum and tuff are reported in Table 1.

2.3. Choice of the operating parameters for ball milling

Steel balls with a density of 7800 kg/m^3 were used. The total load of balls was calculated by the formal fractional mill volume filled by balls (J), using a bed porosity of 0.4. The fractional filling of voids between the balls (U) can be calculated by $U = fc/0.4J$; fc is the formal fractional mill volume filled by

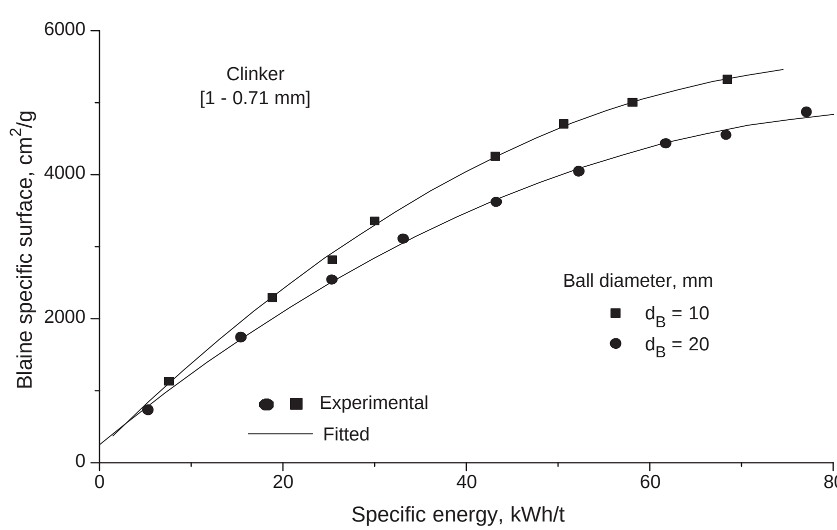

Fig. 1. Blaine specific surface versus specific energy for batch grinding of (1–0.71 mm) cement clinker with 10 and 20 mm ball diameter.

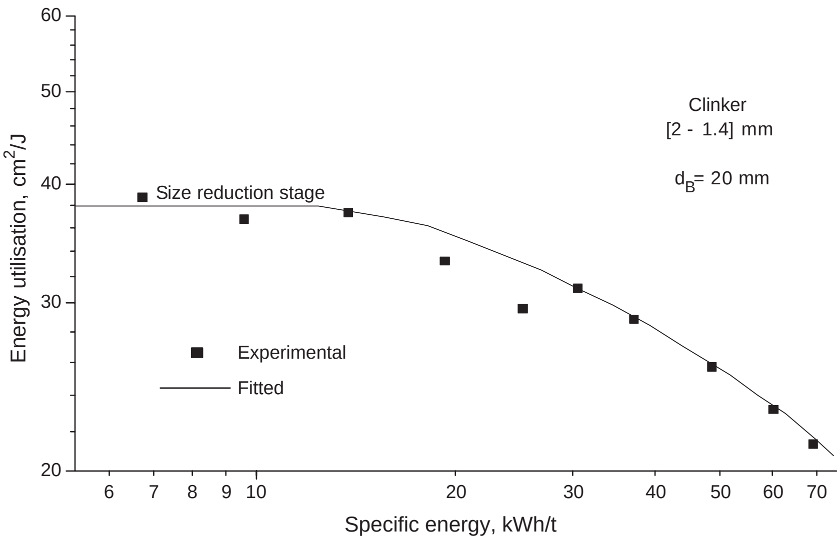

Fig. 2. Energy utilization versus specific energy for batch grinding of (2–1.4 mm) cement with 20 mm ball diameter.

powder using a powder porosity of 0.4 [9]. The ball load distribution composed of grinding balls of 30, 20 and 10 mm was varied (Eq. (2)) according to the Gaudin–Schuhmann distribution equation [10].

$$Q(d_{\mathrm{B}}) = \left(\frac{d_{\mathrm{B}}}{d_{\mathrm{B_{max}}}}\right)^{q} \qquad (2)$$

$Q(d_{\mathrm{B}})$ is the cumulative undersize weight fraction with respect to ball size d_{B}, $Q(d_{\mathrm{Bmax}})$ is the maximum ball size of a given composite grinding media and q is the exponent of the Gaudin–Schuhmann distribution equation taken on a weight basis.

Subsequently, the average ball diameter of composite grinding media $\bar{d}_{\mathrm{B}}$ was calculated by Eq. (3):

$$\bar{d}_{\mathrm{B}} = \sum_{i=1}^{n} d_{\mathrm{B}_i}\left[\left(\frac{d_{\mathrm{B}_i}}{d_{\mathrm{B_{max}}}}\right)^{q} - \left(\frac{d_{\mathrm{B}_{i-1}}}{d_{\mathrm{B_{max}}}}\right)^{q}\right] \qquad (3)$$

where $\bar{d}_{\mathrm{B}_0}=0$.

2.4. Specific surface area characterization

The specific surface was determined by ASTM-C204 Blaine's apparatus. In order to calculate the quantity of material required to make the bed of the permeability cell, the specific gravity of the sample was determined at a few grinding intervals as suggested by Sohoni et al. [11].

3. Results and discussion

The ball mill was initially charged with the grinding media and the feed material. The mill was then running for a definite interval of time, and the torque was recorded during this period. After each grinding period, the mill was stopped, the balls were removed from the mill and mixed powder samples were withdrawn for fineness analysis.

3.1. Blaine specific surface area and specific energy

The change of the Blaine specific surface area versus the specific energy for the clinker size fraction (1–0.71 mm) is shown in Fig. 1. For these runs, mono-sized balls having a diameter of 10 or 20 mm were used keeping constant the other parameters ($J=0.45$, $U=0.8$ and $N=65$ rpm). In a preliminary study, it was shown that the net mill power draw under these operating variables was maximal [12]. The figure shows that the Blaine specific surface increases with increasing specific energy. At a fineness of 3500 cm^2/g, the specific energy is 40 kWh/t for 20 mm ball diameter. The change of the specific surface is affected by the ball size. This effect is significantly pronounced at higher levels of energy input. For a given specific energy consumption, the Blaine specific surface and the energy efficiency concerning this size fraction are greater with 10 mm balls than with 20 mm balls. In a previous study [7] performed with the same clinker on the size class (1–0.71 mm), it was shown that the reduction size rate was maximum with the 20 mm balls. Furthermore, on the basis of an experimental study,

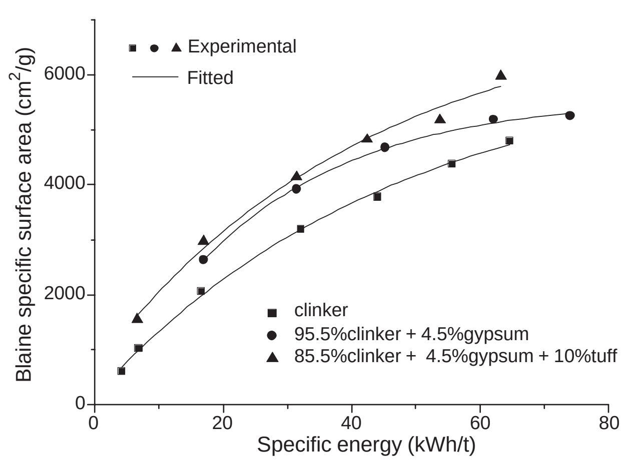

Fig. 3. Blaine specific surface of crude cement clinker feed using additional compounds versus specific energy.

Deniz [13] established the relationships between the specific rate of breakage for various cement materials as function of the feed size and the ball diameter. From this work, it can be calculated that the ball size corresponding to a maximum specific rate of breakage for the initial clinker size class (1–0.71 mm) is also about 20 mm. Now, it is shown that for this feed size interval, a lower breakage rate using 10 mm ball size leads to higher energy efficiency than a maximal breakage rate using 20 mm ball size. Therefore, the later stages of grinding have more importance than the initial stage of size reduction on the total specific energy expended to produce a desired Blaine fineness.

Fig. 2 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 increasing energy consumption. Beyond an average specific energy of 15 kWh/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 losses and dissipation.

Other experiments using crude cement clinker (Table 1) were conducted with an average composite ball size of 25.8 mm (q=2.5). The results of fineness versus specific energy using additional compounds are shown in Fig. 3. It can be seen that gypsum has a considerable effect on the grinding of cement clinker as regards to the product fineness in the range 2500–4500 cm^2/g. The specific energy expended with 4.5% gypsum decreases about 30% compared to the run performed without gypsum. As observed by previous workers [11], the present study confirms that gypsum acts as a very effective grinding aid. The action of this additive has been attributed to its ability to prevent agglomeration and coating of powder on the balls and the mill chamber. The pozzolanic additive (tuff) has a significant beneficial effect on the grinding of cement clinker, especially at high levels of fineness (4000–6000 cm^2/g). The addition of this material to the feed improved the grindability of the clinker. This improvement is put in evidence by the increase of the surface area of the ground composite product with identical specific energy. For a Blaine fineness of 4500 cm^2/g the additional effect of 10% tuff corresponds to a specific energy gain of 10 kWh/t.

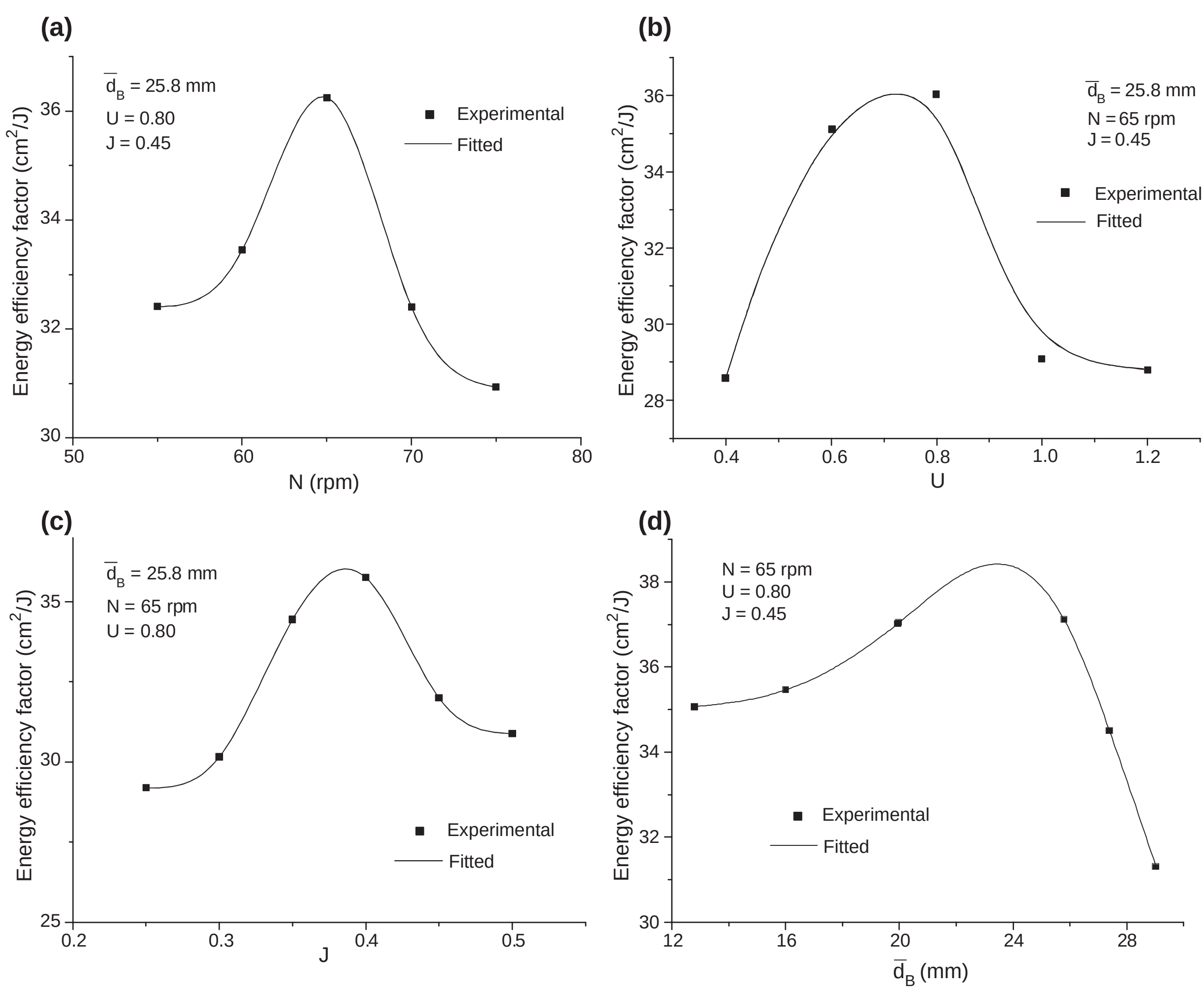

Fig. 4. Effect of mill speed, particle load, balls load and ball size on energy efficiency factor.

3.2. Operating variables and feed charge composition effect on energy efficiency factor

In order to optimize the cement clinker grinding operation, the sensitivity of the energy efficiency factor, defined by the production of 3500 cm^2/g specific surface area per unit of specific energy consumed is studied under various grinding operating conditions and feed charge compositions. It must be noted that most of the experiments were carried out keeping constant the gypsum composition (4.5%). This composition is commonly used in the cement clinker industry. Fig. 4 shows the effect of operating parameters on the energy efficiency factor. Each parameter was varied in turn, keeping the other parameters constant and using crude cement clinker for the feed charge. The mill speed (Fig. 4a), the material load (Fig. 4b) and the ball load (Fig. 4c) have nearly the same effect. The energy efficiency factor increases till a maximum value and decreases then. For these parameters, the maximum value obtained is 36 cm^2/J. The average composite ball size seems to have the strongest effect (Fig. 4d) with a maximum energy efficiency factor value equal to 39 cm^2/J. It is generally observed that the rate of size reduction in tumbling ball mills depends on the rate of collision between the grinding media, the probability of capture of feed particles between the balls and the probability of fracture of the captured particle [14]. Investigating the effects of the powder and ball charge filling on the grinding of quartz in a laboratory ball mill, Shoji et al. [9] found that $U=0.83$ and $J=0.15$ were the optimum conditions for the maximum breakage rate at minimal specific energy consumption. As shown in Fig 4b and c, the optimal grinding values $U=0.75$ and $J=0.38$ obtained for maximal energy efficiency factor are different. These operating conditions probably cause less coating of the powder on the balls and the wall mill. Concerning the effect of the rotational speed (Fig. 4a), the optimum is obtained for $N=65$ rpm (corresponding to about 60% of the critical speed). Yang et al. [15] have reported similar results for runs performed in a laboratory ball mill also equipped with efficient lifter bars for which the fraction of energy available to cause breakage by tumbling is maximal. Moreover, it is shown (Fig. 4d) that the 24 mm optimal ball size corresponding to a maximal energy efficiency factor and concerning the crude material (having more than 50% less than 355 μm) does not coincide with the size calculated by the maximum breakage rate relationships [13]. So, it is concluded again that for this crude cement clinker material the energy efficiency factor can be optimized using operational conditions corresponding to relatively low breakage rates.

Fixing the operational parameters to these optimal values, Table 2 reports the energy efficiency factor for various mass compositions of the coarser cement clinker fraction (2.8–2 mm) in the feed. It is clear that the energy efficiency factor is sensitive to the feed composition. The natural cement clinker feed charge, having 10% of coarser mass fraction is found to be the optimal feed size distribution. This implies that the optimum average ball size is strongly related to the particle size. Therefore, both for closely sieved fractions and crude cement clinker, it is found that an increase of breakage rate can induce a strong increase of fines amount thus promoting agglomeration phenomena between the particles which can slow down the grinding process and lead to an increase of energy consumption for creating new surface.

Table 2
Energy efficiency factor at different mass fraction of cement clinker top size

Energy efficiency factor (cm^2/J)	Fraction % (2.8–2 mm)
31.36	5
36.07	10
30.13	20

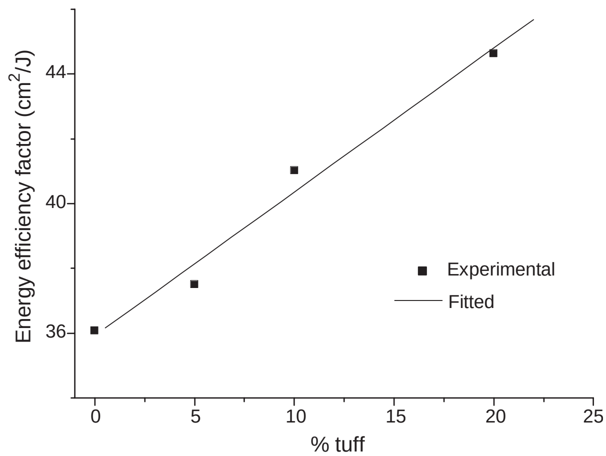

Fig. 5. Effect of additional pozzolanic tuff on energy efficiency factor.

The effect of the pozzolanic additive mass fraction in the cement clinker feed charge is illustrated on Fig. 5. The energy efficiency factor increases linearly as its proportion in the mixture increases. For 20% tuff, the specific energy expended is about 22 kWh/t. Thus, in the context of manufacture of the composite cement, pozzolanic tuff component reduces significantly the specific energy demand.

4. Conclusions

Batch dry grinding tests of cement clinker were performed in a ball mill measuring the power input investigating the effects of operating conditions and material environment on the specific energy.

Gypsum and pozzolanic tuff used as grinding additional compounds improve energy efficiency by decreasing the specific energy for a given Blaine fineness.

For a fineness of 3500 cm^2/g, the optimal operating variables corresponding to a maximal grinding energy efficiency of crude material were found to be: $\bar{d}_B=24$ mm, $N=65$ rpm, $U=0.75$ and $J=0.38$.

In terms of breakage kinetics, this study demonstrates that the energy efficiency of cement finish grinding can be increased by reducing the initial rate of breakage.

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