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EFFECT OF GRINDING AIDS
IN THE CEMENT INDUSTRY
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1. Introduction

The fine grinding of hard materials cannot be just considered a "mechanical" reduction of the original matter into one featuring a certain fineness degree; it is more a complex physical-mechanical operation during which some surface phenomena play an important part.
Despite the development of the grinding technology most cement production still takes place in tubular balls mills, where the effect of grinding aids is of particular evidence. Besides, following the new European directions relevant to the EN 197-1 cements, the consumption of grinding aids has increased considerably because of the wider range of different additions, and greater percentages, allowed in the cement.

2. Cement grinding

The energy efficiency in a ball mill is very low (approx. 5%), since most of the energy is transformed into heat, so that the temperature inside the mill rises from 80 to 100°C.
Local temperatures can even be higher through the impact of the balls on the grains.
Inside the mills there is always a mixture of materials (clinker and additions), which have different grindabilities and properties. Clinker obviously remains the most studied material.
A fresh clinker is more difficult to grind than one which has been stored for a period of 2-3 weeks (Towarow grindability coefficient: 0.9 to 1.15).
It can certainly be stated that the grindability of the clinker:

- decreases if the silica ratio rises;
- is directly proportional to the percentage of Al_2O_3 and Fe_2O_3;
- is proportional to the density of the clinker;
- increases linearly with the alite content;
- improves by increasing lime standard;
- decreases if the belite content rises (according to Towarow, the grindability coefficient varies from 1.10 to 0.70 with 5% or 40% belite respectively);
- is not appreciably affected by alkalis, MgO and free CaO.

Theoretical studies on the maximum ball diameter for the mill charge will not be taken into account, but it can be said that ball diameters between 100 and 110 mm are very seldom used nowadays, and the trend of modern technology is to construct ball mills of large diameter.

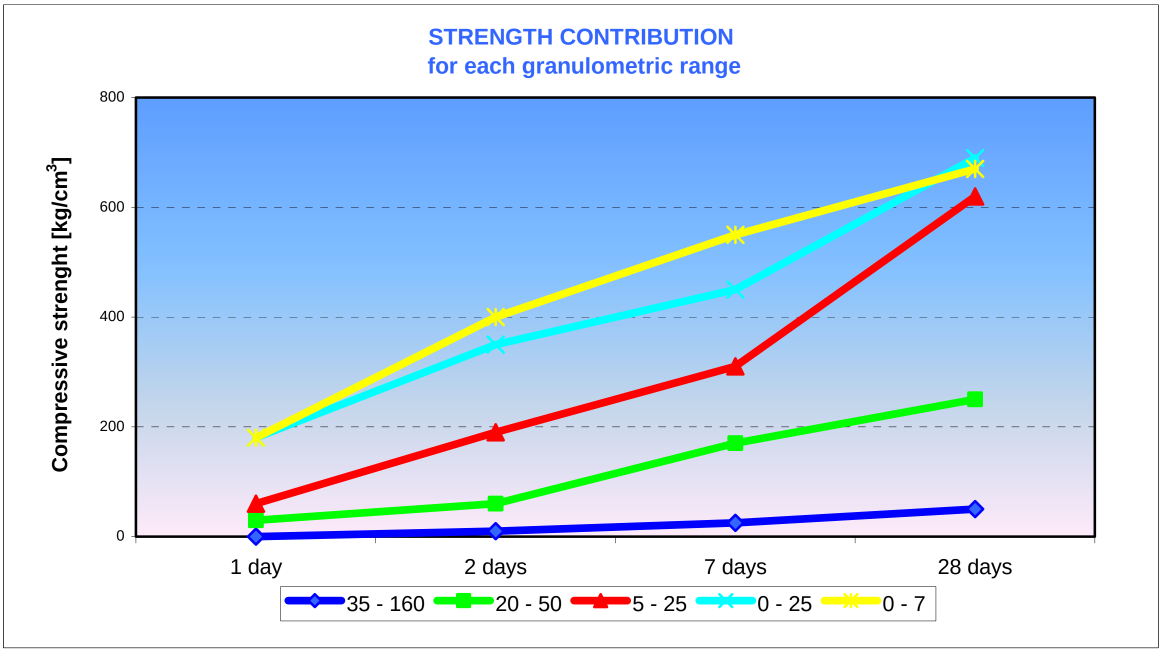
The following law is the basis of every grinding process:
The maximum efficiency occurs when the mill feed fills all voids between the balls.
Murdalier stated that the steel/clinker (s/c) ratio should lie between 8.1 and 10.1.
Scherer mentions an example where the s/c ratio is 8.75, although some authors object that such a ratio may increase to 12 for coarsely ground cements.
The weight of the grinding media in a mill, however, should never be less than 90% of the theoretical charge weight. In cases where additional grinding media are used, half of them should be of a larger size and the other half of the next lower size.

When the mill is operating correctly, there is a continuous rattling of the balls in the first compartment: it should not be rumbling (too much material prevents balls from working properly), or excessively loud (too little material, the s/c is very high). After the mill has been stopped suddenly samples of material can be taken along the axis of the mill from the surface of the grinding media charge, and particle size analysis will provide a basis for evaluating the progress of grinding. The distance between samples should not be greater than 1 m. In the case of a closed-circuit mill the resulting grinding curves will be flatter than for an open-circuit mill.

3. Influence of fineness and granulometric distribution on mechanical strengths

The greater the surface of the hydraulically active components, and therefore the higher the Blaine fineness, the faster does the cement harden.
Nevertheless, the Blaine value only gives an indication and not an absolute value, as it does not adequately reflect the fine fraction which is an important parameter for the grinding process and for the properties of the binder produced.
The fraction between 0 and 7 µm is responsible for high early strengths, whereas the fraction between 0 and 25 µm contributes to strengths at all ages, especially the late ones (Fig. 1).

Fig. 1 - Dependence of the compressive strength during hardening on time and particle size distribution.



It can definitely be stated that the most important, hydraulically active fraction of the cement lies below 40 µm. Larger cement particles hydrate very slowly and their contribution to cement hardening is certainly of minor importance.
It follows that two binders produced from the same raw material, and consequently of the same mineralogical composition, can give remarkably different mechanical strengths although they have the same Blaine fineness.

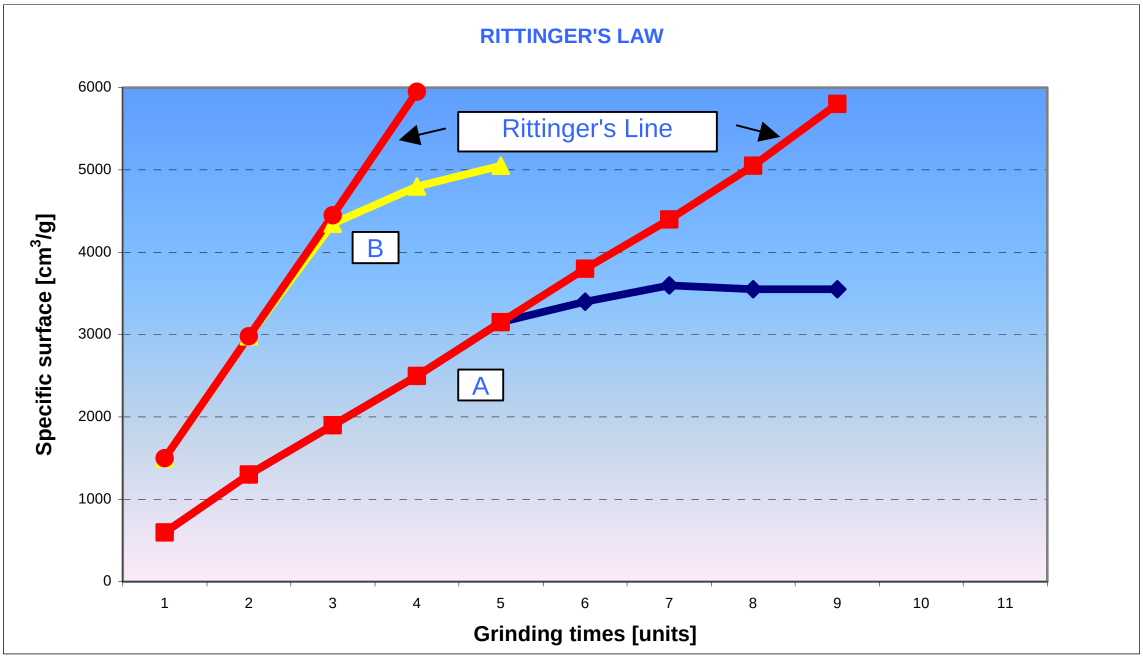
When cement clinker is ground using grinding aids a narrower particle size range is generated, as the percentage of very fine particles, which only influence the setting time, is reduced. This is why the strengths at equal Blaine values are higher than when grinding without grinding aids.
With closed-circuit grinding plants it was also noted that cements ground with heavy circulating loads often contain smaller amounts of both ultra fine and coarse particles. To some extent the grinding aids force the mill to work with a higher circulating load.

4. Grinding aids

4.1 Creation of specific surface and energy required

The increase in the specific surface is related to the energy required for comminution of the particles, and consequently also to the grinding time. This relationship is expressed by Rittinger's law although this is a theoretical derivation and does not consider the energy losses due agglomeration of fine cement particles and for breaking down these agglomerations.
Fig. 2 shows that there are practical deviations from Rittinger's law and that fineness curve tends to reach asymptotic values beyond a certain limit.

Fig. 2 – Rittinger's law and deviations therefrom



It can also be seen from Fig. 2 that clinker "B" shows a slight tendency to the agglomeration, whereas clinker "A" agglomerates more easily.
The action of the grinding media within a rotating mill not only crushes the existing clinker particles, it also sharply compresses them, which leads to the formation of electrostatic surface charges of opposed polarity. The cement particles then agglomerate as a result of the forces of attraction acting on them.
The compression of groups of particles is statistically more likely to take place with fine particles rather than with large particles, and grinding media of large diameter cause greater compression rather those of small diameter.

4.2 Grinding aid application

A step forward in the development was made when the use of grinding aids was introduced, towards the middle of the 1930s. The first step was that of adding coal to the mill feed, but it was soon noticed that this caused a reduction of entrapped air in the concrete, with a consequent serious reduction in the freeze/thaw resistances.
The next step was to add water in such a quantity as not to significantly increase the loss of ignition of the cement produced.
The experience gained showed that polar grinding aids, like water, are the most effective ones. However, the effectiveness of water is limited by its comparatively low polar moment and low molecular weight, despite its high screening effect.

4.3 Grinding aids mechanism of action

Grinding aids act by coating the particles which cause agglomeration with a mono-molecular film which neutralizes the surface electrical charges. Technically speaking, grinding aids provide the charge carriers necessary to satisfy the charges originated by the fracture of the clinker during grinding, thus reducing the tendency to agglomeration. Grinding aids are adsorbed at the fractures surfaces of the particles which have not yet separated, preventing their re-combination under the action of the temperature and pressure.
The mechanism of action of grinding aids can be summarized as follows:

- Elimination of surface electrostatic charge;
- decrease of the energy required for the propagation of micro cracks inside the particles;
- different mechanisms of action, still in study, aimed to explain the positive effect of grinding aids also in context not yet explored.

4.4 Addition of the grinding aid in the mill

The use of grinding aids leads to changes in the grinding process. As soon as the grinding aid was introduced into the first compartment, the following well-known phenomena were observed:

a. The grinding noise significantly increased in the first compartment and decreased in the second compartment; this was due to the immediate reduction of the mill residence time which, in turn, was associated with a reduction of the instantaneous circulating charge and to a remarkable increase in the power consumption by the bucket elevator, as a further confirmation of the sudden emptying of the mill. Under these conditions, with an s/c ratio which rose to values of 15 to 16, the mill can evidently produce coarse ground cement.

b. There is a momentary sharp increase in the circulating load which, however, settles down to a lower level in a few minutes.
In order to restore normal conditions and obtain the maximum advantage from the use of the grinding aid, the setting of the separator has been modified in order to maintain the same Blaine fineness of the cement, with a consequent increase of the circulating load.

c. As regards the performance of the cement produced using grinding aids, an improvement was certainly observed when compared to a conventionally produced cement. Even if the grinding aid employed is a “pure grinding aid”, i.e. without primary effects on the cement performance (setting times, water demand, etc.), strength improvements at equal fineness were recorded thanks to the better granulometry, especially at early ages.

5. Industrial Test: output increase and examination of the mill retention time (MRT)

5.1 Description of the test

The increase in mill output which can be achieved with the use of grinding aids usually range between 10% and 30%, depending on the grinding plant, the materials ground and the required fineness. We are going to show a test made on a "Portland" cement, where excellent results (18,8% increase in production) with a very low admixture dosage (0.02%) were obtained. We will also analyse how it positively affects the grinding process in general and the MRT (Mill Retention Time) in particular.

A tubular, 2-compartment mill, in closed circuit, producing OPC, was examined. Its technical features are listed here under:

Tab. 1

Type of mill :	***Tubular, 2 compartments***		
Mill size :			m 4,0 x 13,0
Compartments size :	First		m 3,70 x 4,03
	Second		m 3,70 x 8,23
Type of separator :	STURTEVANT		1st generation
First compartment	Type of balls	:	Cr-melted 550 HB
	Volume	:	43.3 m^3
Diam. 90 x 18.0	Filling degree	:	27.5 %
Diam. 80 x 18.0	Avg. balls diameter	:	75.3 mm
Diam. 70 x 17.0	Apparent spec. gravity	:	4.445 kg/dm^3
Diam. 60 x 17.0			
Tot. 70.0 t			
Second compartment	Type of balls	:	Cr-melted 600 HB
	Volume	:	88.5 m^3
Diam. 50 x17.25	Filling degree	:	31.8 %
Diam. 40 x17.29	Avg. balls diameter	:	32.9 mm
Diam. 30 x32.78	Apparent spec. gravity	:	4.810 kg/dm^3
Diam. 25 x 34.0			
Diam. 22 x 34.0			
Tot. 135.32 t			

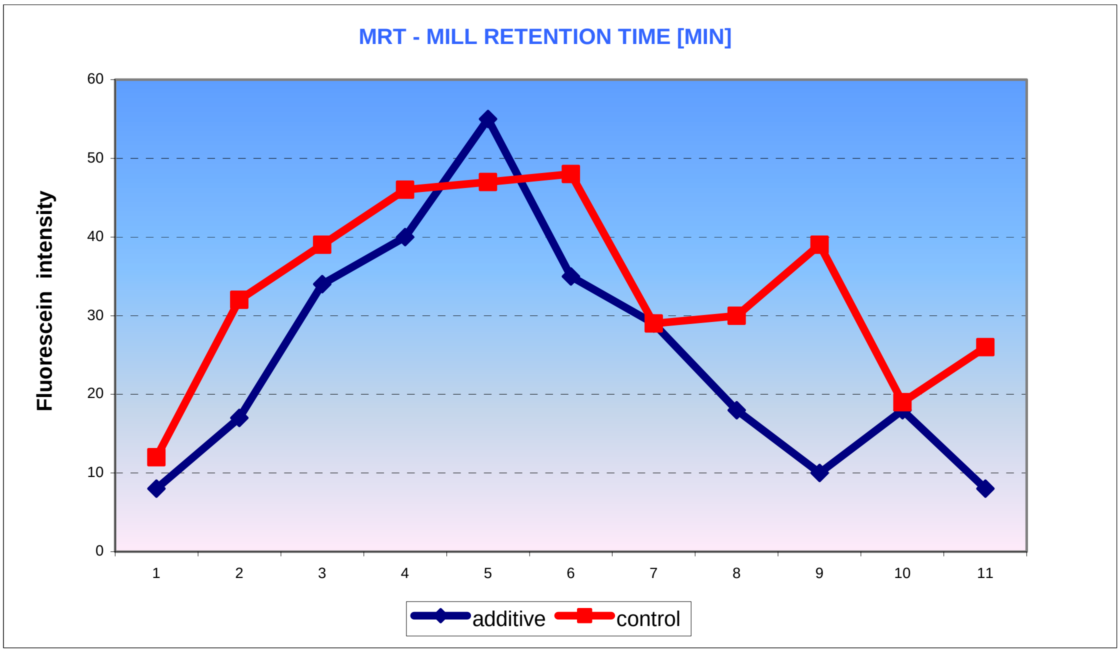
Two 10-days industrial tests were carried out. The first test was a "control" one (i.e. without grinding admixtures), while the second one was carried out with the addition of a grinding admixture sprayed in the mill first compartment.

The charge of the grinding media and the ventilation inside the mill were not varied; we tried to find the mill balance by just changing the operating conditions of the separator and by taking care that cements with an equal specific surface were obtained. The Blaines recorded were: 2,950 cm^2/g for the "blank" cement (control cement) and 2,938 cm^2/g for the "admixtured" cement.

5.2 Mill retention time (MRT)

The MRT represents the average time necessary for the bulk material to pass through the mill. It is a basic parameter for assessing the operating conditions of the plant. Fluorescein was used for the evaluation of the MRT because of its resistance to cement alkalinity, its complete solubility in water and its easy extraction from the cement itself.
Tests with fluorescein have been carried out on a close circuit mill 4x13 m with a separator Sturtevant type. The normal production with grinding aid (0,02%) increased from 80 to 95 t/h. The measurement of the MRT started as soon as the grinding system (mill + separator) reached its equilibrium at 95 t/h. The measurements were carried out both with and without grinding aids.
Fig. 3 shows the results of four tests, carried out with and without GA.

Fig. 3 – MRT – Mill retention time determined by the fluorescein test



The analysis of the retention curve, the maximum of which indicates the average MRT, is often complex and may create some problems in comprehension, but a general examination of the graph will give useful indications on the dynamic of the passage of the material through the mill.
In this case it can be seen that the peak associated with the reference grinding test is flatter at the apex than the peak produced with grinding aid.

The flat part of the reference curve indicates that a part of the material is passing too quickly through the mill (3 minutes), while another fraction remains too long in the mill (7 minutes) and tends to agglomerate. The passage of clinker is consequently not sufficiently compact, i.e. not a uniform mass flow, which is expressed by the increased tendency to agglomeration.
The slight difference in height of the recycle peaks gives a fairly exact idea of the inefficiency of the mill-separator system.
The retention curve plotted during the addition of the grinding aids is substantially different from the one without grinding aid: it is a very sharp curve with an excellent peak and rapid decay of fluorescein.

Tab. 2 – Effects of the grinding aids on MRT

Grinding aid	**---**	***GA***
Dosage		0.02 %
Mill retention time (MRT)	6’	4.6’
Output (t/h)	80	95
Instantaneously circulating load (I.C.C.) in the mill		
I.C.C. = $\frac{\text{M.R.T. (minutes) x E (t/h) x (1+CL)}}{60}$	14.12	18.00
Steel/clinker (S/C)	9.0	10.0
Circulating load (C.L.) $\frac{\Sigma F - \Sigma E}{\Sigma E - \Sigma R}$	0.765	1.475
Separator efficiency = $\frac{\Sigma (100\text{-}F)}{\Sigma (100\text{-}E)} \bullet \frac{1}{CL}$	0.60	0.80
Energy consumption (kWh/t)	40.0	33.7
Mill charge (t)	205.33	205.33

E = Total residue (180, 90, 60, 40, 32 μm) of the separator feeding.
F = Total residue at the same screen mesh sizes of the finished product.
R = Total residue at the same screen mesh sizes of the separator residue.

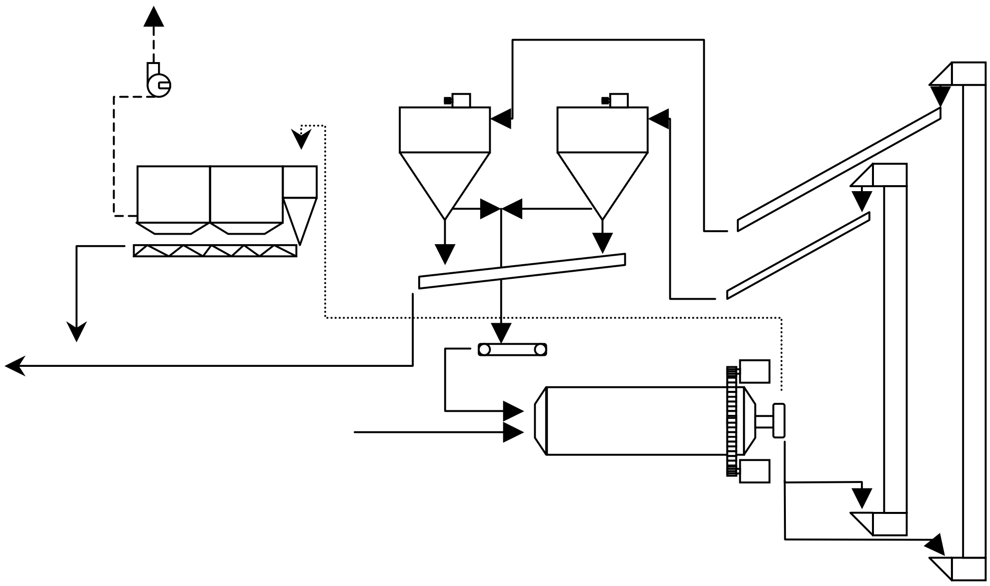
6. Industrial Test: use of a G. A. in a large diameter ball mill

The effects of the grinding aids on the ball mill will be demonstrated by examining a case of use of GA on a slag cement with low fineness. This condition does not normally allow significant mill output increases. Results over the normal average have been obtained, with a mill output increase of 23%.

A one-week industrial test was carried out and the results have been compared with the average results obtained the week before, without grinding aids.
Short-time tests are in fact not to be taken into consideration, as their results are never reliable.

Mill: close circuit two chambers 4,8 x 15,5 m
Power: 2x2.400 kW
Separator: 2 separators Humboldt type 1° gen.
Filter: sleeves 2 chambers + prechamber

Fig. 4 –Mill plant: basic scheme



Cement type: CEM II/A-S 42,5 R

Composition :

Clinker	80%
Slag :	15%
Gypsum:	5%

The test with the grinding aid has been carried out with constant Blaine fineness. The grinding media charge and the ventilation inside the mill were not varied, and the optimum mill operating conditions were achieved by changing the separator parameters, during which care was taken that cements with equal specific surface area were obtained.

		Reference	**With G.A.**
Dosage		-	0,025%
SSBlaine		2870 g/cm^2	2880 g/cm^2
Residuals:90 µm	6,9%	5,1%	
	63 µm	14,8%	10,9%
	40 µm	28,9%	23,6%
	32 µm	36,4%	31,6%
Mill output		104,5 t/h	130,8 t/h

Note: Average values calculated during the production test period

7. Mill ventilation

The efficiency of a ball mill significantly depends on the air speed within the grinding compartments as it affects the speed at which the material passes through; this has to be kept within acceptable time limits in order to prevent excessively coarse particles of material from being swept out of the mill.
In a closed circuit mill the air speed calculated in the free section above the material is of approx. 1.5-2 m/s, and can reach higher values if a static separator is used.

An increase in mill ventilation when grinding aids are used is advantageous only if the de-dusting system suits the new conditions, as the amount of dust is always in greater quantity in such cases.
Fabric filters can also be used for mills with higher level of air ventilation. This also applies to large diameter mills where electrostatic precipitators are frequently replaced with new high-efficiency sleeve filters.

Experience has shown that the dust collecting surface, both for electrostatic precipitators and fabric filters, should be increased by 10 to 15% when grinding aids are used. The installation of a static separator, to be inserted between the mill outlet and the filter, is particularly useful, especially when high flow rates are employed. The coarse particles, swept out of the mill with the air, are intercepted by the static separator and fed to the bucket elevator, while the fine ones are collected in the filter and can then be added to the finished product.

Many cement works have had their separation modernized and mill ventilation systems updated for the use of grinding aids. Table 3 shows some examples.

Tab. 3 – Closed circuit mill

CEMENT PLANT	A	B	C	D
Mill size	5.2 x 16.5 m	3.6 x 10.5 m	3.0 x 8.5 m	3.4 x 10.0 m
Mill motor	6,750 kW	1,900 kW	932 kW	1,300 kW
Adjustments made	• none, i.e. static separator already available	• new static separator • electrostatic precipitator replaced by fabric filter	• new static separator • capacity of fabric filter increased	• new static separator • second fabric filter + new fan
% of increased grinding capacity	26	25	30	35 – 40
% of increased specific power capacity	16	25	15	20 –25
% of improved strengths	8	10	5 – 10	5 – 10
% of lowered cement temperature	10	10	10	10 – 15

8. Technical and economic evaluation of grinding aids

For a complete evaluation of grinding aids, all the technical and economic aspects have to be considered. The technical evaluation is a consequence of a reliable industrial trial, to be performed after laboratory tests. The economic evaluation, to be carried out preferably after the industrial trial, has to consider several factors, that are not always easily quantifiable in terms of money.
The clearest advantage resulting from the use of a grinding aid lies in the increase in the plant output, which then provides a quite easily computable energy saving in terms of money.
The other benefits are less easy to estimate, though sometimes they are most conspicuous than the energy saving. Table 4 shows the main benefits of the use of grinding aids.

Tab. 4 – The most important advantages when using grinding aids

Advantage derived from:	
Production	Increase of the potential output of the plant. Grinding in the most favourable time periods. Easy response to demands peaks.
Quality	Improvement in the product quality with components unchanged. Change in the cement composition with quality unchanged.
Maintenance	Fewer and simpler interventions needed.

8.1 Energy saving

An analysis of the energy saving potential is given; this is often the only parameter employed in evaluating the use of grinding aids.

The following formula calculates the specific energy saving in terms of money S[€/t]:

$$S = \frac{K_e * \alpha - K_a * P}{P * (1 + \alpha)} \quad [€/t] \qquad (1)$$

where:

- P mill output without grinding aid [t/h]
- α mill output increase [%]
- K_e global energy costs (kWh used * kWh cost) [€]
- K_a GA cost (cost/kg * dosage) [€/t]

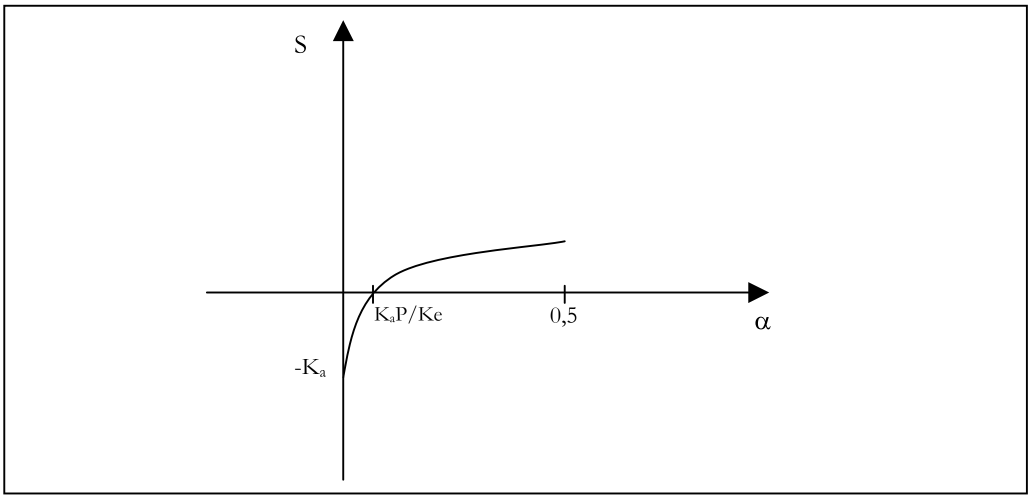
This formula calculates the saving/t of grinded material, in case of:
- mill output increase at the same energy consumption;
- fix cost of energy, without taking in consideration different time courses;
- product with the same quality of the previous one (without additive);
- dosage of grinding aid calculated on the initial mill output (most frequent case)

The minimum increase in output α_{min} on which the saving depends, is calculated as follows:

$$\alpha_{min} = \frac{K_a * P}{K_e} \qquad (2)$$

Function S(α) is shown in Fig. 5 just for the case $0<\alpha<0.5$ (output increase between 0% and 50%). For $\alpha=0$ the saving is negative (i.e. $S=-K_a$ and the additive costs represent a loss). The saving S becomes positive above the value $\alpha=K_a*P/K_e$ and is therefore of major interest to the user.

Fig. 5 - Graph of the specific saving function S (α)

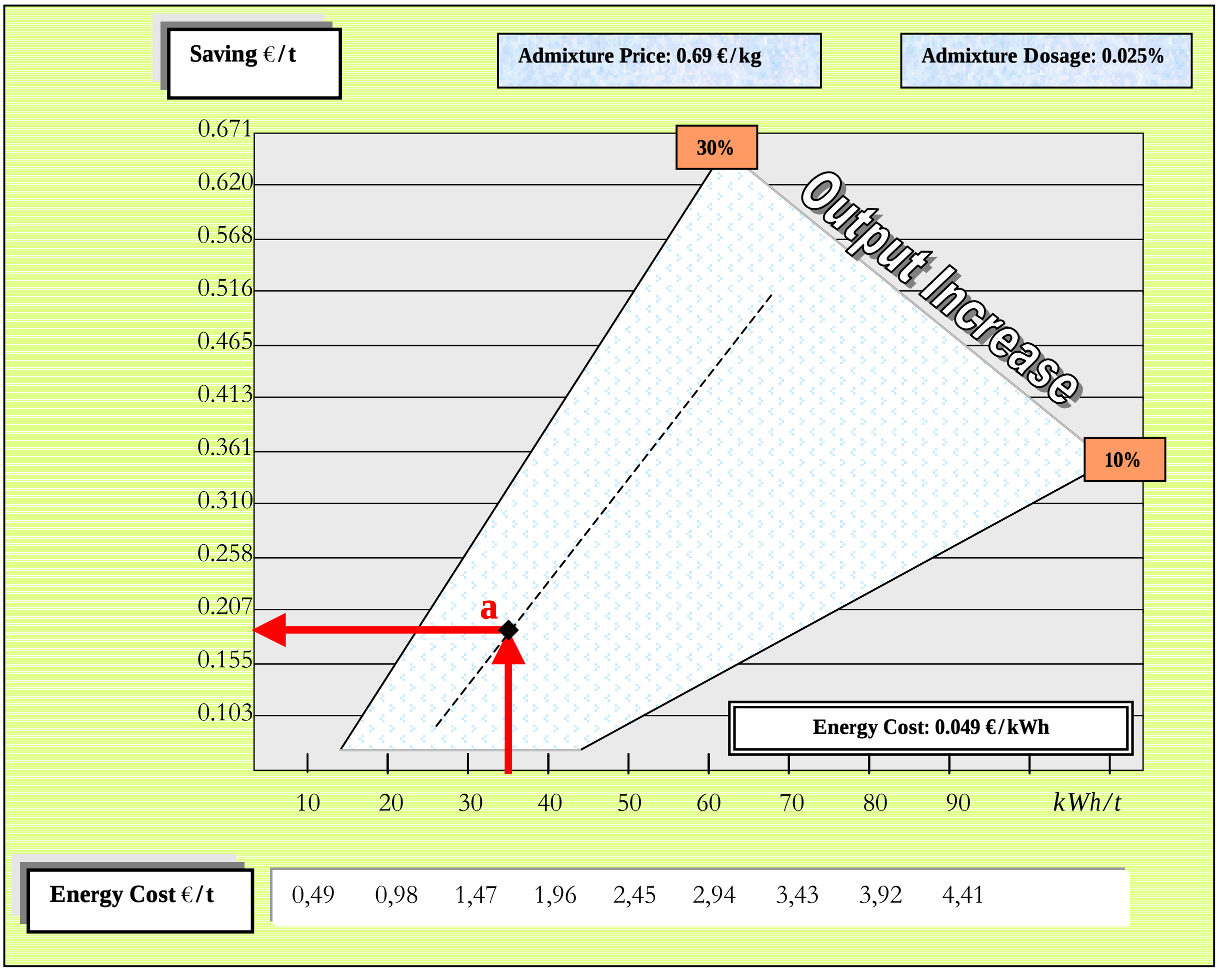


In case the grinding aid dosage is calculated on the new increased mill output, the formula (1) changes as follows:

$$S_1 = \frac{K_e * \alpha - K_a * P * (1+\alpha)}{P * (1+\alpha)} \quad [€/t] \qquad (3)$$

Fig. 6 shows the graph (that can be tailored-made) for the saving calculation [€/t].
Note: The graph has been constructed following the simplified formula: $S_2 = K_e\alpha - K_a$.

Fig. 6 – Graph for the technical-economic evaluation of a grinding aid



The energy cost for a certain cement grinding are shown on the abscissa. The actual savings achieved can be read from the ordinate as a function on the percentage increase in output (dotted area). Point "a" shows the case of energy consumption of 35 kWh/t and mill output increase of 23%. A dosage of G.A. of 0,025% has been considered, with a cost of 0,69 €/kg and energy spending of 0,049 €/kWh. These last parameters could be adapted to specific cases.

8.2 Other advantages

It must be noted that, with the only exception of energy saving that is always considered, other advantages depends on operational conditions and can only be quantified time by time.

8.2.1 Mill output advantage

- Production increase and, consequently, total turnover increase.
- Possibility to grind in cheaper time-course. This allow a decrease in the unit medium cost of energy.

- Better management of high peak demand, thanks to the increased production potential. In this case the additive become a flexible production tool, and not a structural investment.

8.2.2 Quality advantages

- Cement performances improvement, with possibility of better sales and better competition on the market.
- Possibility of production of the same cement, with a saving in clinker addition, and subsequently, in production costs.

8.2.3 Maintenance advantages

- With a higher production more time can be destined to regular maintenance, reducing urgent interventions that are usually quite expensive.
- Better flow of the ground cement in transport and silos, and during truck loading/unloading operations.

9. Conclusions

The examples given show that the use of grinding aids can achieve excellent results with low fineness cements as well as with cements with a high specific surface. Optimisation of the ball charge, as well as a suitable ventilation of the mill, are also essential when grinding aids are used.

The use of grinding aids provides a series of technical and economic advantages.

The main technical advantages can be summed up as follows:

- *Elimination of pack-set phenomena*
- *Increase in output and lower energy consumption*
- *Greater specific surface area (if needed)*
- *Improved cement granulometry*
- *Lower grinding media consumption*
- *Higher separator efficiency*
- *Decrease of mill internal temperature*
- *Better flow of the ground cement in transports and silos, and during truck loading/unloading operations*
- *Better plants flexibility: without structural modifications, the grinding aid affords an "output reserve" ranging between 10% and 30%, to be used according to one's own needs.*

10. Bibliography

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