CEMENT MILLING SIMULATIONS

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Abstract

Cement production is an energy intensive process that consumes a significant portion of world energy. Production costs and environmental concerns are driving the need to use less energy. Up to 40% of total energy for cement production is consumed to obtain the final cement product by dry grinding the cement clinker. Significant optimisation of the traditional cement grinding process can be achieved. Grinding process modelling and simulation methods can be used for the process optimisation. A simulation study conducted using the data from an industrial cement plant indicate that pre-crushing of cement clinker using a Barmac crusher offers realistic benefits to a cement plant. The energy consumption can be reduced in order of 10-15%. Alternatively, throughput increases in the same order can be achieved.

Keywords: Cement milling, energy, optimisation

1. Introduction

From all dry grinding applications, cement clinker is certainly the most important. The current world consumption of cement is about 1.7 billion tonnes per annum and it is increasing at about 1% per annum. Table 1 shows the major cement consumers by countries in 2001 and 2002.
Cement production process typically involves:
- grinding limestone (and other raw materials to achieve the right chemical composition) to about 90% passing 90 microns in a dry circuit,
- making cement by the chemical reaction between the components of the ground mixture which occurs at high temperature in a rotary kiln,

Table 1: Cement consumption (x 1000 metric tonnes)

<table>
<thead>
<tr>
<th>Country</th>
<th>2001</th>
<th>2002</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>626,500</td>
<td>640,000</td>
</tr>
<tr>
<td>India</td>
<td>100,000</td>
<td>100,000</td>
</tr>
<tr>
<td>United States (includes Puerto Rico)</td>
<td>90,450</td>
<td>90,600</td>
</tr>
<tr>
<td>Japan</td>
<td>76,550</td>
<td>75,000</td>
</tr>
<tr>
<td>Republic of Korea</td>
<td>52,012</td>
<td>53,000</td>
</tr>
<tr>
<td>Spain</td>
<td>40,512</td>
<td>40,000</td>
</tr>
<tr>
<td>Italy</td>
<td>39,804</td>
<td>39,000</td>
</tr>
<tr>
<td>Brazil</td>
<td>39,500</td>
<td>40,000</td>
</tr>
<tr>
<td>Russia</td>
<td>35,100</td>
<td>39,000</td>
</tr>
<tr>
<td>Indonesia</td>
<td>31,100</td>
<td>32,000</td>
</tr>
<tr>
<td>Turkey</td>
<td>30,120</td>
<td>31,000</td>
</tr>
<tr>
<td>Mexico</td>
<td>29,966</td>
<td>30,000</td>
</tr>
<tr>
<td>Germany</td>
<td>28,034</td>
<td>28,000</td>
</tr>
<tr>
<td>Thailand</td>
<td>27,913</td>
<td>28,000</td>
</tr>
<tr>
<td>Iran</td>
<td>26,650</td>
<td>28,000</td>
</tr>
<tr>
<td>Egypt</td>
<td>24,500</td>
<td>26,000</td>
</tr>
<tr>
<td>Saudi Arabia</td>
<td>20,608</td>
<td>21,000</td>
</tr>
<tr>
<td>France</td>
<td>19,839</td>
<td>20,000</td>
</tr>
<tr>
<td>Other Countries (rounded)</td>
<td>361,000</td>
<td>360,000</td>
</tr>
<tr>
<td><strong>World Total (rounded)</strong></td>
<td><strong>1,700,000</strong></td>
<td><strong>1,720,000</strong></td>
</tr>
</tbody>
</table>
- grinding the cement clinker nodules to 100% passing 90 microns in a dry circuit.

Approximately one tonne of finished cement is produced from 1.5 tonnes of raw materials. An outline of a common cement grinding flowsheet is shown in Figure 1.

![Figure 1: Outline of typical cement grinding circuit](image)

Production costs and environmental concerns are emphasizing the need to use less energy and therefore the development of more energy efficient machines for grinding and classification. The electrical energy consumed in the cement making process is approx. 110 kWh/tonne. Energy consumption in each stage of the production process is given as percentages in Figure 2.

2. CEMENT GRINDING SIMULATION

To simulate the potential benefits of clinker pre-crushing, standard Bond grinding calculations were used as well as modelling and simulation techniques. The platform used for simulations was JKSimMet simulation software and the models for the cement mills were obtained from literature (Benzer et al, 2001, Benzer et al, 2003). Mill power simulations were carried out using Morell’s power model for tumbling mills (Morrell, 1998)
2.1. Bond method

The established technique for determining power requirements for ball mills is by applying Bond’s equations (Bond, 1961) or some adaptation of them such as described by Rowland (1972).

Bond’s equation for the specific power requirement to reduce a feed with a specified feed $F_{80}$ to a product with a specified $P_{80}$ is given below:

$$W = W_i \left( \frac{10}{\sqrt{P_{80}}} - \frac{10}{\sqrt{F_{80}}} \right)$$

where:
- $W$ is specific motor output power (kWh/t),
$W_i$ is the Work Index (kWh/t),
$P_{80}$ is sieve size passing 80% of the mill product (ım),
$F_{80}$ is sieve size passing 80% of the mill feed (ım),

Equation 1 is modify it with a range of “efficiency factors” which attempt to cater for the differences in feed and operating conditions that are found with different circuit designs and ore types. These are dry grinding, open circuit ball milling, mill diameter, oversize feed, grinding finer than 75 microns and too large or too small reduction ratios.

For this study, the dry grinding ($EF_1$), mill diameter ($EF_3$), oversize feed ($EF_4$) and fine product ($EF_5$) factors are relevant. Therefore, the equation for the specific power requirement is:

$$W = EF_1 \cdot EF_3 \cdot EF_4 \cdot EF_5 \cdot W_i \left( \frac{10}{\sqrt{P_{80}}} - \frac{10}{\sqrt{F_{80}}} \right)$$  \hspace{1cm} (2)

The dry grinding factor $EF_1$ accounts for inefficiencies related to dry grinding and it is equal to 1.3.

The diameter factor was introduced by Bond due to what he stated was an increase in mill efficiency as the diameter increased above 8ft. The specific power using equation 1 is multiplied by $EF_3$ where the mill diameter exceeds 8ft. Rowland (1972) modified the application of $EF_3$ and stated it should be used up to mills of 12ft then kept at the 12ft value for all larger mills.

$$EF_3 = (8/D_{ft})^{0.2} = \left( \frac{2.44}{D} \right)^{0.2}$$  \hspace{1cm} (3)

where:
$D_{ft}$ is the mill diameter inside liners (ft)
$D$ is the mill diameter inside liners (m)

The $EF_4$ oversize feed factor was stated by Bond to cater for those cases where the feed size was coarser than a specific size limit ($F_0$), which was a function of ore hardness. Bond argued that if the feed ore were coarser than
this, bigger balls would be needed to break the coarser feed particles at the expense of finer grinding of smaller particles. Conversely, if smaller balls were used to grind the finer particles they would not break the coarser particles. Either way a grinding inefficiency would result. The $EF_4$ factor is applied only when the $F_{80}$ is greater than $F_0$ and has a value greater than 1. The specific power is multiplied by $EF_4$.

The correction factor $EF_4$ for the ore feed size is calculated as follows (Rowland, 1982):

$$EF_4 = \left[ R_r + (W_i - 7) \left( \frac{F_{80} - F_0}{F_0} \right) \right] / R_r$$

(4)

$$P_0 = 4000 \left( \frac{13}{W_i} \right)^{0.5} \text{ for ball mills}$$

(5)

$$R_r = \frac{F_{80}}{P_{80}}$$

(6)

where:
- $R_r$ size reduction ratio
- $F_0$ optimum mill feed size (im),
- $F_{80}$ actual mill feed size (im),
- $P_{80}$ mill product size (im),

From equation (3) an optimum clinker feed size for the first mill compartment ($W_i=15.0$ kWh/t) is calculated, $P_0 = 3.72$ mm. The correction factor is therefore applied for coarser feed sizes.

The correction factor $EF_5$ for the products finer than 75 $\mu$m (Rowland, 1982) is determined as follows.

$$EF_5 = \frac{P_{80} + 10.3}{1.145*P_{80}}$$

(7)
2.2. Modeling and Simulation

The mathematical modelling of any grinding circuit consists of four distinct phases:

1) Development of the basic model structure of each unit process. The models used is generally mechanistic, i.e. they describe the important mechanisms which are thought to be operating, but contain a number of unknown parameters whose numerical values must be adjusted to tune the model to a particular plant.

2) Collection of extensive plant survey data, which are obtained by sampling and fully sizing all the streams in the circuit, recording plant operating conditions and measuring mass flows and other relevant information. If necessary, the survey data are adjusted using mathematical techniques to produce best estimates of the measured values (mass balancing).

3) Tuning model parameters to the plant survey data. This is done by searching for the set of parameters that will best reproduce each set of survey data. This stage often also involves regression of the estimated parameter values against operating conditions. This work is invariably carried out by computer because of the complex numerical procedures required.

4) Computer simulations aimed at optimising plant operation or predicting the effect of changes in circuit configuration. This is done by linking unit models together in a computer program, whose inputs are the circuit feed and operating conditions, and which predicts the characteristics of all streams (including final product) in the grinding circuit.

In the area of dry grinding, mathematical models for ball mills, air swept ball mills and air separators have been developed (Austin et al, 1984; Zhang, Y 1992, Benzer et al, 2001). Such models have been used to simulate dry grinding behaviour and have assisted in the design of circuit configurations.
2.2. Ball Mill models

The perfect mixing ball mill model considers the comminution device to be perfectly mixed. The feed to a comminution machine is transformed into product, provided that nothing happens within the machine to change the operating conditions. It applies to wet or dry machines and to machines breaking fine or coarse particles.

Similarly, it will not apply to very long ball mills, such as are used for clinker grinding, because of segregation of balls and because the particles become finer as they move down the mill. So, rod mills and long ball mills must be regarded as perfectly mixed mills in series. The concept of perfect mixing still applies but a significant consideration is the physical characteristics of the mill. For example, the rod mill is regarded as a series of perfectly mixed mills with the classification and selection functions, or rates of discharge and breakage, changing systematically from mill to mill.

As described in the literature (Lynch at all, 1977, Napier-Munn at all, 1996), a perfect mixing ball mill can be illustrated by the following equation:

\[ f_i + \sum_{j=1}^{i} \left[ \frac{a_{ij} r_i p_j}{d_i} \right] = p_i + \frac{r_ip_i}{d_i} \]  

where:
- \( f_i \) = feed rate of size fraction \( i \) (t/h)
- \( p_i \) = product flow of size fraction \( i \) (t/h)
- \( a_{ij} \) = the mass fraction of size that appear at size \( i \) after breakage
- \( r_i \) = breakage rate of particle size \( i \) (h\(^{-1}\))
- \( s_i \) = amount of size particles inside the mill (tonnes)
- \( d_i \) = the discharge rate of particle size (h\(^{-1}\))

The model consists of two important functions, the breakage function \( a_{ij} \) that describes the material characteristics and breakage/discharge rate function \( (r_i/d_i) \) which defines the machine characteristics and can be calculated when feed and product size distribution are known and breakage function is available. Most \( r_i/d_i \) for ball mills lie on a smooth curve that can be fitted to a
spline function with four knots.

In this study the first compartment of the cement mill was modelled as two perfect mixing ball mills in series followed by a screen which mimics the function of the diaphragm. The second compartment is modelled as one ball mill. The schematic of the model is shown in Figure 3.

![Figure 3. Two compartment cement mill model](image)

Air classifiers are modelled using the efficiency curve approach. The mathematical model selected is capable of defining “fish hook” type efficiency curves. The general form of the equation is presented below:

\[
E_0 = C^* \left[ \frac{(1 + \beta \cdot \beta^* \cdot X) \cdot (\exp(\alpha) - 1)}{\exp(\alpha \cdot \beta^* \cdot X) + \exp(\alpha) - 2} \right]
\]  

(9)

Where:

- \( X = \frac{d_i}{d_{50c}} \)
- \( \beta = \) parameter which determines the initial rise of the efficiency curve
- \( \beta^* = \) parameter determined for \( E_0 = C/2 \)
- \( \alpha = \) sharpness of classification, determines the slope at \( d = d_{50c} \)
- \( d_{50c} = \) corrected cut size
- \( C = \) fines fraction reporting to fine product
3. SIMULATION RESULTS

3.1. Bond method

The Bond method is used to calculate the required milling power to produce 110 t/h of OPC cement, 3200 Blaine for different clinker feed sizes. Efficiency factors for dry grinding $EF_1=1.3$, fine grinding $EF_5=1.11$ and for the mill diameter $EF_1=0.914$ were kept constant in all calculations. Table 3 shows the calculated milling power requirements with raw clinker ($F_{80}=15.5$ mm) and with pre-crushed clinker ($F_{80}=4.5$, 3.0 and 1.8 mm) using a Barmac crusher.

It can be seen that a reduction in power in the order of 9–15% is calculated for different crushed clinker feed $F_{80}$ sizes. Corresponding to the change in factor $EF_4$, a 5-6% reduction comes from improving the milling efficiency with finer feed. In order to get this improvement, the ball charge size distribution in the first compartment needs to be adjusted for finer feed.

3.2. Modelling and simulation results

The modelling of the clinker grinding was carried out using the principles described earlier. It should be noted that in order to obtain the “site specific” model constants, detailed surveys of the milling circuit are required. The size distribution of the material in each stream is required, as well as from different points inside the mill (Benzer et al., 2001). The base case flowsheet generated in the JKSimMet grinding simulation software is shown in Figure 4. As explained in previous sections, the first compartment was modeled as two ball mill in series, diaphragm between the first and second compartment was

<table>
<thead>
<tr>
<th>$F_{80}$ (mm)</th>
<th>$EF_4$</th>
<th>Power required (kW)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.5</td>
<td>1.06</td>
<td>3564</td>
<td>0.0</td>
</tr>
<tr>
<td>4.5</td>
<td>1.01</td>
<td>3251</td>
<td>8.8</td>
</tr>
<tr>
<td>3.0</td>
<td>1</td>
<td>3133</td>
<td>12.1</td>
</tr>
<tr>
<td>1.8</td>
<td>1</td>
<td>3018</td>
<td>15.3</td>
</tr>
</tbody>
</table>

Table 3. Bond method calculation results
presented as a screen and the second compartment is presented as one ball mill. Information given in the flowsheet is solids throughput (t/h), 80% passing size and % passing 0.01 mm.

Using the above base case model, simulations with different feed size distributions (raw clincer and precrushed clincer using the Barmac crusher) were carried out, keeping the product size constant at 0.038 mm. The resulting increase in throughput is shown in Table 4. It can be observed that significant increases in throughput were predicted. The increase was bigger than using the Bond method.

Potential benefits from using the Barmac crusher to pre-crush the cement clinker before milling in terms of increased throughput are summarised in Table 5. It should be noted that this result does not consider any circuit physical limitations such as conveying, aeration, air classifier capacity etc. The accuracy of the predictions is strongly related to the accuracy of the Barmac product size distributions supplied for this study.

![Figure 4. Greens Island base case simulation flowsheet](image-url)
It can be observed that Bond calculations gave less throughput increase than JKSimmet simulations. This could be because the JKSimMet simulation results may have been overoptimistic as separator performance was kept the same. The model capable to simulate changes in performance with different air separator loads is not available at present.

4. Conclusions

Production costs and environmental concerns are emphasizing the need to use less energy for cement production. Up to 40% of total energy is consumed to obtain the final cement product by dry grinding the cement clinker. Significant optimisation of the traditional cement grinding process can be achieved. Grinding process modelling and simulation methods can be used for optimisation. A simulation study conducted using the data from an industrial cement plant indicate:

- Pre-crushing of cement clinker using a Barmac crusher offers realistic benefits to a cement plant.

<table>
<thead>
<tr>
<th>Feed F80 (mm)</th>
<th>minus 75 microns in Barmac product (%)</th>
<th>Percentage throughput increase, Bond method</th>
<th>Percentage throughput increase, JKSimMet</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.5</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4.5</td>
<td>12.1</td>
<td>9.1</td>
<td>13.6</td>
</tr>
<tr>
<td>3</td>
<td>15.4</td>
<td>14.3</td>
<td>22.7</td>
</tr>
<tr>
<td>1.8</td>
<td>20.5</td>
<td>18.2</td>
<td>27.3</td>
</tr>
</tbody>
</table>
The energy consumption can be reduced in order of 10-15%.
Alternatively, throughput increases in the same order can be achieved,
providing there is no other capacity limitations in the circuit.

References

   Handbook, Norman L. Weiss, Editor in Chief.
2. F.C.Bond, Crushing and Grinding Calculations Parts I and II,
   British Chemical Engineering, 6(1961)(6-8)
3. F.C.Bond, Crushing and Grinding Calculations
   Additions and Revisions. Allis-Chalmers Manufacturing Co.,
4. F.C.Bond, Standard Grindability Test Tabualted., Transaction
   AIME, 183(1949)313.
5. C.A.Rowland, Jr. & Kjos, D.M. “Rod and Ball Mills” in Mineral
   Processing Plant Design, Ch.12, pp. 239-278.
   mill performance using Bond Work Index to measure grinding
7. C.A. Rowland, Grinding Calculations Related to the Application of
   large Rod and Ball Mills. Allis-Chalmers Publication 22P4704.
9. H. Benzer, L. Ergun, M. Oner and A.J. Lynch, Case Studies of
   Models of Tube Mill and Air Separator Grinding Circuits, Proceedings:
   XXII International Mineral Processing Congress, Chief Editors: L.
10. A.J.Lynch at all Mineral Crushing and Grinding Circuit –
    Their Simulation, Optimisation, Design and Control. Amsterdam,
    Mineral Comminution Circuits - Their Operation and Optimisation.
    Brisbane, Julius Kruttschnitt Mineral Research Centre (1996).