Material Mix Control in Cement Plant Automation

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The objective of this article is the development of a novel raw material mix proportion control algorithm for a cement plant raw mill, so as to maintain preset target mix proportion at the raw mill outlet. This algorithm utilizes one of the most basic and important tools of numerical linear algebra, the singular value decomposition (SVD), for calculation of raw mix proportion. The strength of this algorithm has been verified by comparing the results of this method with that of the results of the QCX-software developed by F.L. Smidth of Denmark, a pioneer in cement plant automation, on a 2500 tons-per-day (tpd) dry process cement plant situated at Jayanthipuram, Andhra Pradesh, India.

Introduction

The cement manufacturing process consists broadly of mining, crushing and grinding, burning, and grinding with gypsum. This is shown in Fig. 1. Two basic processes, the wet process and the dry process, are used for cement manufacturing. In the wet process, proper proportions of the raw materials are mixed with enough water to form a paste called *slurry*. In this form the raw materials are further proportioned, mixed, ground and pulverized, and then pumped into a rotary, inclined furnace, called a *kiln*. The dry process is similar, except that the raw materials are proportioned, stored, ground, mixed, pulverized, and fed into the kiln in a dry state. Inside the kiln the raw mix will undergo a sequence of reactions [1,2]. Sintering takes place at the final stage of the reaction, i.e., at 1400-1450° C, and a substance called *clinker*, having its own physical and chemical properties, is formed. The clinker is cooled, crushed, and mixed with a predetermined percentage of gypsum to regulate the setting time of cement. Finally, the finished product, known as the portland cement, is stored in large storage bins called silos, from which it is fed to an automatic packing machine.

In this article a dry cement process is considered. The raw materials for cement production are limestone, silica, iron, and bauxite. A single raw material is seldom found with the required proportions of raw materials; thus, a measured proportion of the raw materials is used, in order to give the desired chemical and mineralogical composition to the clinker. The clinker of desired chemical composition is expected to satisfy the following modules related to the chemical composition of the raw mix:

- Lime Saturation Factor (LSF):

$$\mathrm{LSF} = \frac{\mathrm{CaO} \times 100}{2.8\ \mathrm{SiO_2} + 1.2\ \mathrm{Al_2O_3} + 0.65\ \mathrm{Fe_2O_3}} \qquad (1)$$

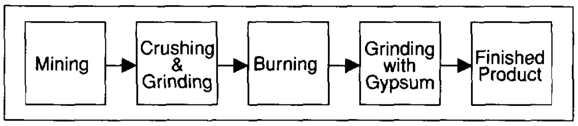

Fig. 1. Block schematic of cement process.

* Silica Modulus (SM):

$$\mathrm{SM} = \frac{\mathrm{SiO_2}}{\mathrm{Al_2O_3} + \mathrm{Fe_2O_3}} \qquad (2)$$

* Alumina Modulus (AM):

$$\mathrm{AM} = \frac{\mathrm{Al_2O_3}}{\mathrm{Fe_2O_3}} \qquad (3)$$

A high LSF requires high heat consumption for clinker burning inside the kiln, and thus gives more strength to the cement. A higher SM decreases the liquid phase content, which impairs the burnability of the clinker and reduces the cement setting time. The value of AM determines the composition of liquid phase in the clinker.

The goal is to achieve a desired level of LSF, SM, and AM of the raw mix, to produce a particular quality of the cement by controlling the mix proportions of the raw materials. To achieve an appropriate raw mix proportion is very difficult, due to the inconsistencies in the chemical composition of the raw material.

This article is concerned with the design, development, and testing of a raw material mix proportion control for a cement plant raw mill. A systematic design method is given for raw mix proportion control which accounts for the dead time of the grinder, as well as the minimum and maximum capacity limit of feeders and servo motors. This control mechanism can be used in a raw mill with any number of weigh feeders. The control algorithm relies on the use of the robust singular value decomposition (SVD) method for all numerical calculations.

System Description and Problem Statement

System Description

The raw mill grinder receives raw materials such as limestone, silica, iron, and bauxite for the production of cement clinker in separate feeders, called weigh feeders. All the raw materials are ground in a raw mill grinder to a powder form. A sample of this ground raw mix is collected at the output of the raw mill grinder by an auto sampler, and a sample is prepared after being finely ground by a vibration mill and pressed by

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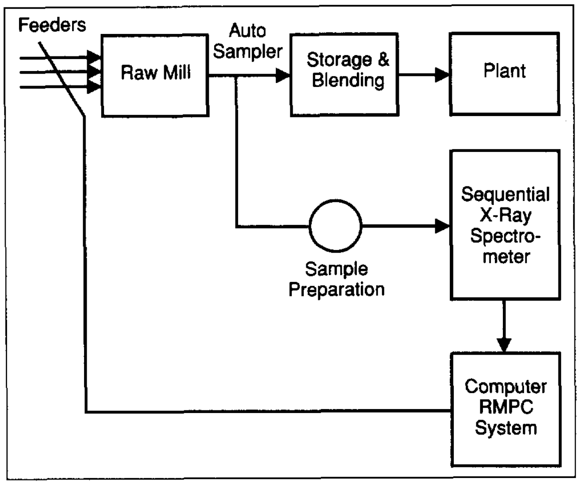

Fig. 2. Block schematic of raw mill processing steps.

hydraulic press, and then is analyzed in the laboratory by an X-ray sequential spectrometer. The results of the X-ray analysis, which are obtained through sampling and analyzing the equipment, are fed to the computer through a data communication line, for the required control action; the entire process is illustrated in Fig. 2.

Problem Statement

When all the analyzed raw mix composition data are available, one must design and develop the raw mix proportion control algorithm which will calculate the proportionating ratio of each raw material and will give the results to the ratio setters (controllers) of the feeding equipments as set values, so that a desired quality of clinker can be produced.

Singular Value Decomposition

Singular value decomposition(SVD) [3-7], is one of the most basic and important tools in the analysis and solution of the problems in numerical linear algebra, and is finding increasing applications in control and digital signal processing. The potential of the SVD technique is first exploited in the domain of linear algebra, where it provides a reliable determination of the rank of the matrix, thereby leading to accurate solutions of linear equations. The SVD was established for real square matrices by Beltrami and Jordan in 1870, for complex square matrices by Autonne in 1902, and for general rectangular matrices by Eckart and Young [4] in 1939.

Raw Mix Proportion Control Algorithm

In this section we develop the control algorithm based on the SVD method. The purpose of this algorithm is to calculate the change in raw materials in each of the weigh feeders to achieve the target value of the chemical composition or moduli, i.e., LSF, SM, AM.

Suppose at any instant the action of the control system gives rise to the composition change as dLSF′, dSM′, and dAM′ in response to the required composition change of dLSF, dSM, and dAM, respectively. Then the total mean squared error at that instant will be

$$E = (dLSF - dLSF')^2 + (dSM - dSM')^2 + (dAM - dAM')^2. \quad (4)$$

The problem now is to minimize E with respect to the change in the feeder content (dW_i; $i = 1, 2, \ldots n$). Differentiating equation (4) with respect to dW and equating to zero, we will have dLSF′ = dLSF, dSM′ = dSM, and dAM′ = dAM. As mentioned earlier, the values of LSF, SM, and AM of the raw material change constantly. Our objective is to keep the values of LSF, SM, and AM of the raw mix at the raw mill outlet fixed by changing the quantity of the raw material in the weigh feeders. So the moduli LSF, SM, and AM are functions of the change in the raw material in different feeders. This can be represented as

$$dLSF' = dLSF = \sum_{i=1}^{n} \frac{\partial LSF}{\partial W_i} dW_i \quad (5)$$

$$dSM' = dSM = \sum_{i=1}^{n} \frac{\partial SM}{\partial W_i} dW_i \quad (6)$$

$$dAM' = dAM = \sum_{i=1}^{n} \frac{\partial AM}{\partial W_i} dW_i \quad (7)$$

$$\sum_{i=1}^{n} dW_i = 0.0 \quad (8)$$

$$LL_i \leq dW_i \leq HL_i \quad (9)$$

where W_i is the mix ratio of raw material in the feeder, and LL_i and HL_i are the lower limit and higher limit of the raw material change possible for the *i*th feeder, respectively.

The composition change, for example in LSF, is given by

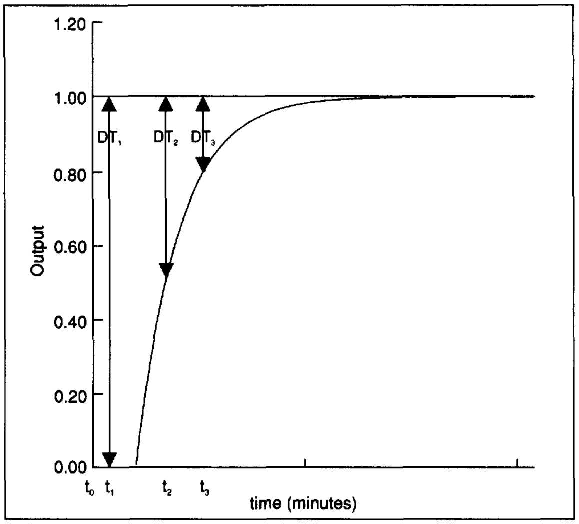

Fig. 3. Response of raw mill for unit change of input.

$$dLSF' = LSF_{SP} - LSF_{Meas}. \qquad (10)$$

Here SP stands for set point, i.e., the desired value, and Meas stands for measured, i.e., the value achieved, and Equation (8) states that the sum of raw mix proportion is equal to 100%. The measured composition change values in response to a control action can be available after considerable time delay due to the grinder inertia, sample collection, and preparation. To take this into account, the process dead time constant has included:

$$dLSF' = LSF_{SP} - LSF_{Meas} + DT, \qquad (11)$$

where DT is the process dead time compensation. Fig. 3 shows the dead time compensation at raw mill outlet for step input change, where DT_1, DT_2, and DT_3 are dead time constants at t_1, t_2, and t_3 instants of time, respectively. For vertical raw mill grinders this value can be assumed to be zero.

Table 1. Summary of Raw Mix Proportion Control Algorithm for Dry Composition of Raw Mix

STEP 1:
BEGIN:
Find the intermediate Set Point (SP) values for each of the modules as per Equation (12):
$(Mod)_{ISP} = (Mod)_{SP} + (\Delta Mod)$,
where

$(\Delta Mod)_{SP} = a\, e_n + b\,(e_n - e_{n-1}) + c\,(\sum_i e_i \frac{Q_T}{\sum_i Q_i})$, *and Mod denotes modulus with a, b, and c, scalar constants,* $e_n = (LSF_{SP} - LSF_{Meas})_n$ *is the error at nth time instant, and* Q_T *is the total feed rate during the entire analysis period.*

STEP 2:
Calculate the process dead time compensation value from the knowledge of the process characteristics.

STEP 3:
Compute the composition change as in Equation (14):
$dMod' = Mod_{SP} - (Mod)_{Meas} + DT + \Delta Mod_{SP}$.

STEP 4:
Calculate the elements of the differential coefficient matrix as in Equation (20).

STEP 5:
Form the matrix D.

STEP 6:
Compute the pseudoinverse of the matrix D by SVD technique:
$D^{\#} = V \Sigma U^T$.

STEP 7:
Calculate the raw mix proportion change as in Equation (22):
$dw = (V \Sigma U^T)\, d$.

STEP 8:
Check for the constraints to be satisfied by dw as in Equation (9). If satisfied, then go to STEP 10.

STEP 9:
Set the value of dw not satisfying the constraints in Equation (9) to its limiting value and go to STEP 5.

STEP 10:
Check for the feeder capacity.
If it exceeds the limit, set the feeder raw mix proportion at maximum limit and the change in raw mix proportion at the required value.
Go to STEP 5.

STEP 11:
Give the values of dw_i.

END:

To achieve the desired SP values for the moduli at the minimum time we have used an intermediate SP value (ISP) which varies as per a PID control algorithm in the manner SP = SP + ΔSP, so that for LSF case, we have

$$LSF_{ISP} = LSF_{SP} + \Delta LSF_{SP}, \qquad (12)$$

where

$$\Delta LSF_{SP} = a\, e_n + b(e_n - e_{n-1}) + c\left(\sum_i e_i \times \frac{Q_T}{\sum_j Q_j}\right), \qquad (13)$$

with a, b, and c, scalar constants, $e_n = (LSF_{SP} - LSF_{Meas})$ is the error at *n*th time instant, and Q_T is the total feed rate during the entire analysis period.

Thus, the change in composition for LSF at the *n*th time instant is

$$dLSF' = LSF_{SP} - LSF_{Meas} + DT + \Delta LSF_{SP}. \qquad (14)$$

The composition change can be calculated similarly for other moduli.

Now consider the solution of Equations (5) to (8). Here we have at best four equations, and the number of unknowns is the same as the number of weigh feeders. If there are four feeders then we have the following set of equations with four unknowns:

$$\frac{\partial LSF}{\partial W_1} dW_1 + \frac{\partial LSF}{\partial W_2} dW_2 + \frac{\partial LSF}{\partial W_3} dW_3 + \frac{\partial LSF}{\partial W_4} dW_4 = dLSF' \qquad (15)$$

$$\frac{\partial SM}{\partial W_1} dW_1 + \frac{\partial SM}{\partial W_2} dW_2 + \frac{\partial SM}{\partial W_3} dW_3 + \frac{\partial SM}{\partial W_4} dW_4 = dSM' \qquad (16)$$

$$\frac{\partial AM}{\partial W_1} dW_1 + \frac{\partial AM}{\partial W_2} dW_2 + \frac{\partial AM}{\partial W_3} dW_3 + \frac{\partial AM}{\partial W_4} dW_4 = dAM' \qquad (17)$$

$$dW_1 + dW_2 + dW_3 + dW_4 = 0.0 \qquad (18)$$

Rearranging equations (15) to (18) in matrix form yields

$$\begin{bmatrix} \frac{\partial LSF}{\partial W_1} & \frac{\partial LSF}{\partial W_2} & \frac{\partial LSF}{\partial W_3} & \frac{\partial LSF}{\partial W_4} \\ \frac{\partial SM}{\partial W_1} & \frac{\partial SM}{\partial W_2} & \frac{\partial SM}{\partial W_3} & \frac{\partial SM}{\partial W_4} \\ \frac{\partial AM}{\partial W_1} & \frac{\partial AM}{\partial W_2} & \frac{\partial AM}{\partial W_3} & \frac{\partial AM}{\partial W_4} \\ 1 & 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} dW_1 \\ dW_2 \\ dW_3 \\ dW_4 \end{bmatrix} = \begin{bmatrix} dLSF' \\ dSM' \\ dAM' \\ 0.0 \end{bmatrix} \qquad (19)$$

or

$$\mathbf{D\,dw} = \mathbf{d} \tag{20}$$

or

$$\mathbf{dw} = \mathbf{D}^{-1}\mathbf{d} \tag{21}$$

where **D** is the differential matrix, **dw** is the raw mix proportion change matrix, and **d** is the composition change matrix.

If the number of feeders is more than or less than four, then the number of unknowns will change accordingly, giving rise to an overdetermined or underdetermined solution. In this case

$$\begin{aligned}\mathbf{dw} &= \mathbf{D}^{\#}\mathbf{d} \\ &= (\mathbf{U}\,\Sigma\,\mathbf{V}^{\mathbf{T}})^{\#}\,\mathbf{d} = (\mathbf{V}\,\Sigma\,\mathbf{U}^{\mathbf{T}})\,\mathbf{d},\end{aligned} \tag{22}$$

where # denotes the pseudoinverse of the indicated quantity. The solution dw_i should also satisfy the constraints given in Equation (9). If a value of dw is out of the stated limit, then that particular value will be clipped at the limiting value, thereby decreasing the number of unknowns. If it is a four-feeder case with one-feeder contents clipped at its limiting value (i.e., the feeder content is known), this will give rise to a set of four equations with three unknowns, for which the SVD is applied for solution. This set of four equations with three unknowns constitutes an overdetermined set of equations, and the SVD method is a better candidate for its solution [4]. This process is continued until a valid solution is obtained. Similar cases will arise if the raw mix proportion in a particular feeder exceeds its maximum capacity.

All calculations to follow are made for dry composition of the raw mix. With known moisture content of the raw materials, the wet proportions can be calculated using the following formulae:

$$\text{Wet proportion} = \frac{X_i}{\sum_i X_i} \times 100, \tag{23}$$

where $X_i = \dfrac{\text{Dry proportion}}{1 - 0.01 \times (\%H_2O)_i}$..

Even without considering the percentage of water content of each raw material, the results of this algorithm remain close to that of the case of wet proportions. The above procedure is summarized in Table 1.

If the stacker reclaimer, a machine that feeds limestone of constant chemical composition to the weigh feeders, is available, then the LSF value will more or less remain constant. So in this case, one must give importance to achieving desired values for SM and AM. To cope with this situation in our method one can simply ignore Equation (15). Also our method can be used in the event of feeder failure, or the addition of a feeder. In these cases, the number of feeders is simply changed and the corresponding equations, similar to Equation (15), are added or deleted as appropriate.

Next we outline the procedure to compute the differential matrix. Here the element value is the amount of change for that modulus with unit change in raw material mix proportion into the grinder. This can be obtained from the calculation of the composition of the raw materials, but in cement production processes the composition of the raw materials fed into the mill changes constantly. So it is not possible to get fixed values for these differential factors. Raw materials from a particular quarry have the composition varying over a very narrow range. So for our purpose we have chosen a typical composition of raw materials with its values as the average value of the material received from the quarry. The raw materials in each feeder as given in the next section, consist of CaO, SiO2, Al2O3, and Fe2O3, thus affecting all the three moduli such as LSF, SM, and AM as given in Equations (1), (2), and (3). So these moduli can now be redefined as

$$\mathrm{LSF} = \frac{\sum_{i=1}^{n} \mathrm{CaO}_i \cdot W_i}{\sum_{i=1}^{n}\left(2.8(\mathrm{SiO_2})_i \cdot W_i + 1.2(\mathrm{Al_2O_3})_i \cdot W_i + 0.65(\mathrm{Fe_2O_3})_i \cdot W_i\right)} \tag{24}$$

$$\mathrm{SM} = \frac{\sum_{i=1}^{n} (\mathrm{Si_2O_3})_i \cdot W_i}{\sum_{i=1}^{n}\left((\mathrm{Al_2O_3})_i \cdot W_i + (\mathrm{Fe_2O_3})_i \cdot W_i\right)} \tag{25}$$

$$\mathrm{AM} = \frac{\sum_{i=1}^{n} (\mathrm{Al_2O_3})_i \cdot W_i}{\sum_{i=1}^{n} (\mathrm{Fe_2O_3})_i \cdot W_i} \tag{26}$$

where n is the number of feeders. Now the differential coefficients of Equations (15), (16), and (17) can be obtained by differentiating the Equations (24), (25) and (26) with respect to W_i. The differential coefficients are calculated in the next section.

Implementation and Results

A computer control routine has been developed using C++, an object-oriented programming language, in an Intel 80486-based PC-AT under the DOS environment. This software package consists of three modules, the communication, control algorithm, and user interface. The results of this control method have been compared over an extended period of time with that of the QCX results of F.L. Smidth (FLS) of Denmark, in a 2500 tons-per-day (tpd) dry-process cement plant situated at Jayanthipuram, Andhra Pradesh, India, which is commissioned by FLS. The raw mill of this plant has three feeders with a vertical grinder. Samples are collected by an auto sampler, and the sample is prepared and analyzed by an X-ray spectrometer in the QCX (quality control X-ray) department. The materials in three different feeders have the following composition:

Feeder No.	CaO percentage	SiO2 percentage	Al2O3 percentage	Fe2O3 percentage
1	46.00	12.20	1.60	0.60
2	0.341	8.897	37.25	28.30
3	0.746	22.50	16.31	46.73

Table 2. Comparison of the Results of FLS QCX-Method and SVD-Based RMPC

Time (p.m.)	FLS QCX-program				SVD-based RMPC			
	F1	F2	F3	Total Matl.	F1	F2	F3	Total Matl.
	percentage			tons	percentage			tons
6	93.39	4.44	2.26	237	—	—	—	—
7	94.68	2.88	2.45	235	—	—	—	—
8	93.43	4.29	2.28	225	95.24	2.43	2.37	235
9	93.55	3.22	3.23	223	94.27	3.49	2.24	225
10	93.56	4.18	3.26	230	93.49	3.37	3.14	223
11	93.62	3.24	3.13	230	93.05	4.79	3.16	230
12	—	—	—	—	93.14	3.69	3.17	230

To calculate differential factors we picked a particular instant when the three feeders were carrying 214, 9, and 1.5 tons of raw materials, respectively. Then we have

$$\frac{\partial LSF}{\partial W_1} = -0.0005768, \quad \frac{\partial LSF}{\partial W_2} = 0.0111755, \quad \frac{\partial LSF}{\partial W_3} = 0.0143808$$

$$\frac{\partial SM}{\partial W_1} = -0.0060575, \quad \frac{\partial SM}{\partial W_2} = 0.1258084, \quad \frac{\partial SM}{\partial W_3} = 0.1091692$$

$$\frac{\partial AM}{\partial W_1} = -0.0014775, \quad \frac{\partial AM}{\partial W_2} = 0.0145116, \quad \frac{\partial AM}{\partial W_3} = 0.1236642$$

The set points for these moduli are LSF = 1.16, SM = 2.3, and AM = 1.1.

The data taken for the testing of this method are from the log book of Jayanthipuram cement plant on March 8, 1993, from 6 p.m. to 11 p.m., and the control actions by this method (RMPC denotes "raw mix proportion control") and FLS QCX-program are given in Table 2.

Our results are based on the condition that the SM and AM set points will be achieved simultaneously, ignoring the LSF set point case. This is because the FLS QCX program results are based on the condition of achieving SM set point by 100% and AM set point by 50%. These priority assignment facilities exist in the FLS QCX-program, whereas our program always gives 100% importance to moduli and depends on two previous SP values to calculate the errors. For this reason, in Table 2 the control actions are given from 8 p.m. to 12 midnight. The values of the PID constants are a = 0.1, b = 0.1, and c = 0.0. The maximum feeder capacities are 250, 15, and 15 tons, respectively. These results are consistent with many other similar runs.

Conclusion

This article presents a novel raw mix proportion control system. To demonstrate the efficacy of this method the results are compared with that of FLS of Denmark. The distinct features of the control algorithm are that it

- works for any number of feeders
- is highly flexible and easily adaptable to new situations
- operates on PID control strategy, giving faster response
- is easy to implement in any new plant or any change of the raw material by mere change of differential factors
- takes care of the process dead time delays
- takes into account the limiting values for feeder capacity and control action
- is highly economical

This package not only can be applied for raw mix proportion control but also can be used for all types of grinding and blending operations, such as coal pulverization mills, to obtain coal with a desired level of ash content.

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