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Computer control of cement raw mill with an improved material mix control scheme

A. K. SWAIN and B. SUBUDHI

A particular quality of cement in a cement plant can primarily be maintained by controlling the raw mix proportion at raw mill outlet. The raw mix proportion control is a very difficult task due to the constantly varying composition of the available raw materials. This paper deals with the design, development and testing of a novel raw material mix proportion control algorithm for a cement plant raw mill, so as to maintain the preset target mix proportion at the raw mill outlet. This algorithm utilizes the potentiality of partial singular value decomposition (PSVD) technique, which is three times faster than the classical SVD, for the calculation of raw material mix proportion. The strength of this algorithm has been verified after testing on a 2500 tons per day (tpd) dry process cement plant situated at Jayanthipuram, Andhra Pradesh, India.

1. Introduction

1.1. Cement process

The entire cement manufacturing process [1,7] as shown in Fig. 1, consists essentially of grinding the raw materials, mixing them intimately in certain proportions and burning in a large rotary inclined furnace, called a kiln, at a temperature of approximately 1300 to 1500°C, where the materials sinter and partially fuses into balls known as *clinker*. The clinker is cooled and ground to a fine powder, with a predetermined percentage of gypsum added to regulate the setting time of cement. The mixing and grinding of raw materials can be done either in water, giving rise to a wet process or in a dry state, giving rise to a dry process.

In this paper, a dry cement process is considered. Here the raw materials are crushed and fed into the grinding mill in correct proportions, where they are dried and ground to a fine powder known as *raw meal*. The raw meal is then pumped to the blending silo for blending, to obtain a uniform and intimate mixture, by means of compressed air. Uniform distribution of raw materials is essential for a uniform product, and also the intimate

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The authors are with the Indira Gandhi Institute of Technology, Sarang, Orissa, India-759 146; A. K. Swain was formerly with Ramco Industries Limited, Madras, India.

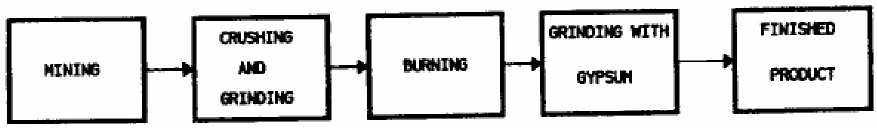

Figure 1. Block schematic of cement process

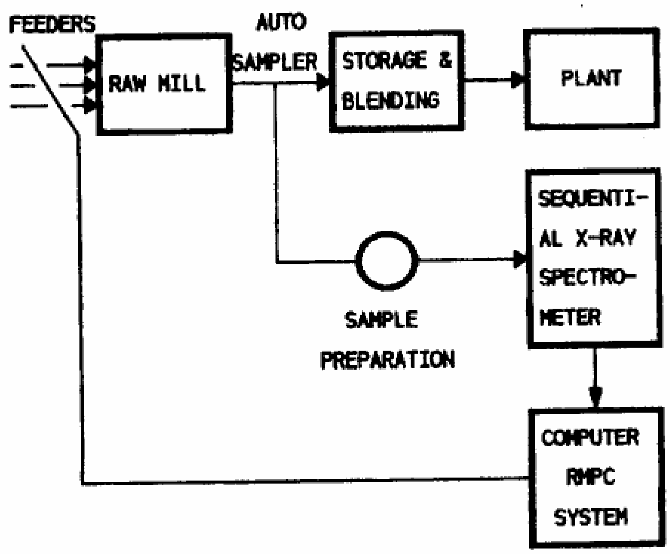

Figure 2. Block schematic of the raw mill processing steps

mixture of the materials ensure proper reaction in the kiln. The lay out of the raw mill is shown in Fig. 2.

1.2. Raw material mix proportion control

The raw materials used in the manufacture of portland cement consist mainly of lime, silica, iron oxide and alumina. Apart from these, coal ash is added during raw meal burning, and gypsum during the grinding of clinker. A single raw material is seldom found with required proportions of raw materials, so a measured proportion of the raw materials are used, in order to give the clinker, the desired chemical and mineralogical composition. The clinker of desired chemical composition is expected to be fulfilled on satisfying the following modules on behalf of the chemical composition of the raw material mix:

- Lime Saturation Factor (*LSF*):

$$LSF = \frac{CaO \times 100}{2.8SiO_2 + 1.2Al_2O_3 + 0.65Fe_2O_3} \tag{1}$$

- Silica Modulus (*SM*):

$$SM = \frac{SiO_2}{Al_2O_3 + Fe_2O_3} \tag{2}$$

- Alumina Modulus (AM):

$$AM = \frac{Al_2O_3}{Fe_2O_3} \tag{3}$$

A desired level of LSF, SM and AM of the raw material mix is required to be achieved to produce a particular quality of cement. It is very difficult to achieve an appropriate raw material mix proportion due to the inconsistencies in the chemical composition of the available raw material.

In this paper a systematic design method for an improved raw material mix proportion control (IRMPC) is described, which is an improvement over the raw mix proportion control (RMPC) algorithm given by Swain [10, 11], in addition to this the IRMPC accounts for the moisture content in the raw material and loss on ignition (LOI) of each raw material and coal ash. The LOI is the extent of carbonation and hydration of free lime (CaO) and free magnesia on exposing cement to atmosphere. This control mechanism can be used in a raw mill with any number of weigh feeders. The control algorithm uses the robust partial singular value decomposition (PSVD), a modified version of the classical singular value decomposition (SVD) [5-11] method for all numerical calculations.

2. Raw material mix control system

The raw mill grinder receives raw materials such as lime stone, 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 grinded raw material mix is collected at the output of the raw mill grinder by an auto sampler, a sample is prepared after being finely ground by a vibration mill, pressed by hydraulic press, and is then analyzed in the laboratory by an X-ray sequential spectrometer. Then the X-ray analysis results are fed to the computer through a data communication line for the required control action; the entire process is illustrated in Fig. 2. Then the computer control action is fed to the ratio setters (controllers) of the feeding equipment as set values, so that a desired quality of clinker can be produced.

3. Problem formulation

After receiving the analyzed raw material mix composition data, one must design and develop a control algorithm, we call it an improved raw material-mix proportion control (IRMPC) algorithm, which will calculate the proportionating ratio of each raw material to produce a clinker of a specific chemical moduli along with the following features

- Maximum and minimum capacity limit of each feeder, and servo motor

- Dead time and inertia of the grinder
- Inclusion of additional feeders or exclusion of existing feeders
- Water content of each raw material
- Loss on ignition (LOI) of each raw material and coal ash

4. Raw material mix proportion control algorithm

The raw material mix of a particular chemical composition or moduli, that is, LSF, SM and AM, will produce a particular quality of cement. In addition to the raw meal, the clinker contains coal ash formed during the burning of raw meal in precalciner and kiln. Hence, the raw meal composition will be different from clinker composition, which needs to convert the available raw material composition to its clinker equivalent by dividing each component with the factor, what we call is clinker-raw meal conversion factor ($CRCF$), it is defined as

$$CRCF = 1 - \frac{\text{LOI of the material}}{100}$$

Also the maximum absorption of coal ash in clinker on LOI free basis must be calculated, which is given by

$$\begin{aligned}&\text{Coal ash absorption in clinker (LOI free basis)} = \\ &= (\text{percentage of ash in coal}) \times \frac{\text{Kiln Heat Consumption}}{\text{Calorific Value of Coal}} \times \\ &\times \left(1 - \frac{\text{LOI of Coal Ash}}{100}\right)\end{aligned}$$

At any instant of time if the control action for the change in moduli are $\mathrm{d}LSF$, $\mathrm{d}SM$ and $\mathrm{d}AM$, respectively, the total mean squared error at that instant will be

$$E = (\mathrm{d}LSF - \mathrm{d}LSF')^2 + (\mathrm{d}SM - \mathrm{d}SM')^2 + (\mathrm{d}AM - \mathrm{d}AM')^2 \tag{4}$$

The problem now is to minimize E with respect to the change in the feeder content ($\mathrm{d}W_i; i = 1, 2, \ldots n$). The coal ash added during the burning of raw meal is not fed by any feeder, but for mathematical convenience it is so assumed. Differentiating equation (4) with respect to dW and equating to zero, we will have

$$\mathrm{d}LSF' = \mathrm{d}LSF = \sum_{i=1}^{n} \frac{\partial LSF}{\partial W_i}\mathrm{d}W_i + \frac{\partial LSF}{\partial W_c}\mathrm{d}W_c \tag{5}$$

$$\mathrm{d}SM' = \mathrm{d}SM = \sum_{i=1}^{n} \frac{\partial SM}{\partial W_i}\mathrm{d}W_i + \frac{\partial SM}{\partial W_c}\mathrm{d}W_c \tag{6}$$

$$\mathrm{d}AM' = \mathrm{d}AM = \sum_{i=1}^{n} \frac{\partial AM}{\partial W_i}\mathrm{d}W_i + \frac{\partial AM}{\partial W_c}\mathrm{d}W_c \tag{7}$$

$$\sum_{i=1}^{n} \mathrm{d}W_i + \mathrm{d}W_c = 0.0 \tag{8}$$

$$LL_i \leqslant \mathrm{d}W_i \leqslant HL_i \tag{9}$$

where W_i is the raw material in the i-th feeder, W_c is the equivalent coal ash in the fictitious feeder, and LL_i, HL_i are the lower limit and higher limit of the raw material change possible for i-th feeder, respectively. As $\mathrm{d}W_c$ can not be controlled directly, hence its value is taken as the maximum absorption of coal ash in clinker, as its differential coefficients are constants, which gives rise to a constant term, called coal ash constant, represented by CA.

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

$$\mathrm{d}LSF' = LSF_{\mathrm{SP}} - LSF_{\mathrm{Meas}} \tag{10}$$

Here SP stands for Set Point, that is, the desired value, and Meas stands for Measured, that is, 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 delay constant has been included:

$$\mathrm{d}LSF' = LSF_{\mathrm{SP}} - LSF_{\mathrm{Meas}} + DC \tag{11}$$

where DC is the process delay compensation. Fig. 3 shows the delay compensation at raw mill outlet for step input change, where DT_1, DT_2 and DT_3 are delay 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.

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 $\mathrm{SP} = \mathrm{SP} + \Delta\mathrm{SP}$, so that for LSF case, we have

$$LSF_{\mathrm{ISP}} = LSF_{\mathrm{SP}} + \Delta LSF_{\mathrm{SP}} \tag{12}$$

where

$$\Delta LSF_{\mathrm{SP}} = ae_n + b(e_n - e_{n-1}) + c\Big(\sum_i e_i \times \frac{Q_T}{\sum_j Q_j}\Big) \tag{13}$$

with a, b and c, scalar constants, $e_n = (LSF_{\mathrm{SP}} - LSF_{\mathrm{Meas}})_n$ is the error at n-th time instant, Q_T is the total feed rate of the raw mill during the entire analysis period, and Q_j is the feed rate at j-th instant of the above analysis period.

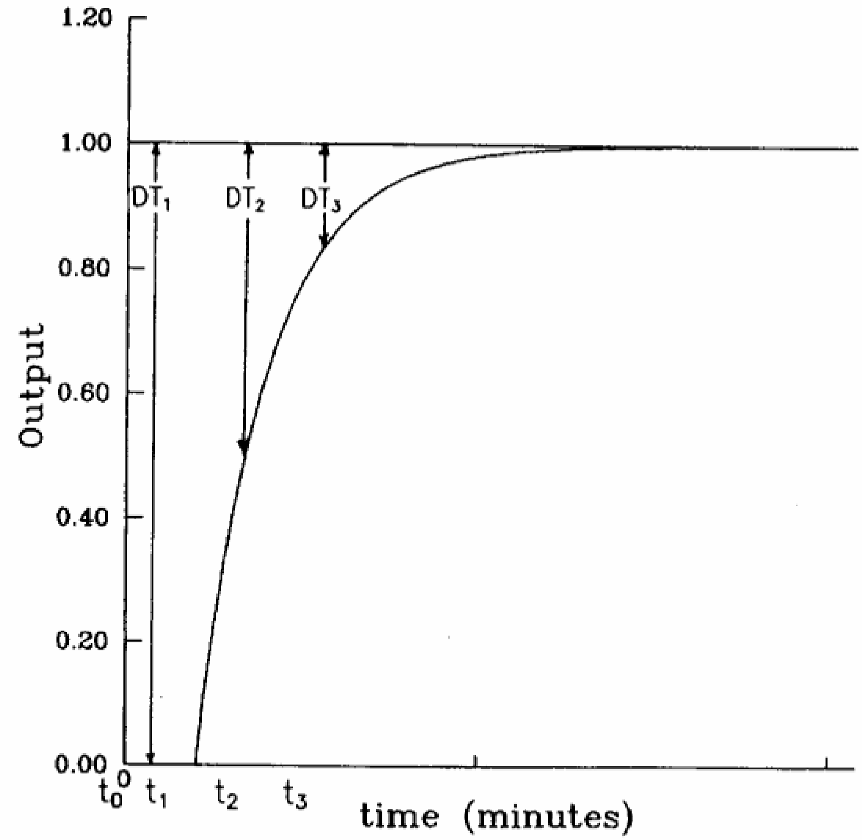

Figure 2. Response of raw mill for unit change of input

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

$$dLSF' = e_n + DC + \Delta LSF_{SP} \tag{14}$$

The composition change can be calculated similarly for other moduli.

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

$$\frac{\partial LSF}{\partial W_1}dW_1 + \frac{\partial LSF}{\partial W_2}dW_2 + \frac{\partial LSF}{\partial W_3}dW_3 + \frac{\partial LSF}{\partial W_4}dW_4 = dLSF' - CA_1 \tag{15}$$

$$\frac{\partial SM}{\partial W_1}dW_1 + \frac{\partial SM}{\partial W_2}dW_2 + \frac{\partial SM}{\partial W_3}dW_3 + \frac{\partial SM}{\partial W_4}dW_4 = dSM' - CA_2 \tag{16}$$

$$\frac{\partial AM}{\partial W_1}dW_1 + \frac{\partial AM}{\partial W_2}dW_2 + \frac{\partial AM}{\partial W_3}dW_3 + \frac{\partial AM}{\partial W_4}dW_4 = dAM' - CA_3 \tag{17}$$

$$dW_1 + dW_2 + dW_3 + dW_4 = -CA_4 \tag{18}$$

Where CA_i is the coal ash constant for the i-th feeder. Rearranging equations (15) to (18) in the matrix form yields

$$\begin{bmatrix} \frac{\partial LSF}{\partial W_1} & \frac{\partial LSF}{\partial W_2} & \frac{\partial LSF}{\partial W_3} & \frac{\partial LSF}{\partial W_4} \\ \frac{\partial SM}{\partial W_1} & \frac{\partial SM}{\partial W_2} & \frac{\partial SM}{\partial W_3} & \frac{\partial SM}{\partial W_4} \\ \frac{\partial AM}{\partial W_1} & \frac{\partial AM}{\partial W_2} & \frac{\partial AM}{\partial W_3} & \frac{\partial AM}{\partial W_4} \\ 1 & 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} \mathrm{d}W_1 \\ \mathrm{d}W_2 \\ \mathrm{d}W_3 \\ \mathrm{d}W_4 \end{bmatrix} = \begin{bmatrix} \mathrm{d}LSF'' \\ \mathrm{d}SM'' \\ \mathrm{d}AM'' \\ -CA_4 \end{bmatrix} \tag{19}$$

$$\text{or,} \qquad \boldsymbol{D dw} = \boldsymbol{d} \tag{20}$$

$$\text{or,} \qquad \boldsymbol{dw} = \boldsymbol{D}^{-1}\boldsymbol{d} \tag{21}$$

where $\boldsymbol{D}$ is the differential matrix, $\boldsymbol{dw}$ is the raw material mix proportion change matrix, $\boldsymbol{d}$ is the composition change matrix, and $\mathrm{d}LSF'' = \mathrm{d}LSF' - CA_1$, $\mathrm{d}SM'' = \mathrm{d}SM' - CA_2$ and $\mathrm{d}AM'' = \mathrm{d}AM' - CA_3$.

The above solution for $\boldsymbol{dw}$ in equation (21) is valid only if the differential matrix $\boldsymbol{D}$ is square and non-singular. If the number of feeders is not four and the three moduli are required to be satisfied simultaneously, then this results in a rectangular differential matrix, which may either be an overdetermined (number of feeders less than four) or underdetermined (number of feeders greater than four). In this case, it may so happen that equation (20) has a multitude of solutions or no solution at all. If $\boldsymbol{D}$ happens to be non-singular then it may result in ill-condition matrix, which leads to numerical instability during computation of its inverse. For any overdetermined, underdetermined or ill-conditioned system, PSVD guarantees a unique solution [8-11]. Then, the general form of solution for $\boldsymbol{dw}$ can be represented by

$$\boldsymbol{dw} = \boldsymbol{D}^{\#}\boldsymbol{d} \tag{22}$$

where $\boldsymbol{D}^{\#}$ is called the *Moore-Penrose* inverse or *pseudo-inverse*, which can be defined as

$$\boldsymbol{D}^{\#} = (\boldsymbol{D}^T\boldsymbol{D})^{-1}\boldsymbol{D}^T; \quad \text{for } \boldsymbol{D} \text{ an overdetermined matrix}$$

and

$$\boldsymbol{D}^{\#} = \boldsymbol{D}^T(\boldsymbol{D}\boldsymbol{D}^T)^{-1}; \quad \text{for } \boldsymbol{D} \text{ an underdetermined matrix}$$

where ^{T} stands for transpose of matrix.

The solution for $\boldsymbol{dw}$ in equation (21) and (22) gives the raw material proportions on LOI free basis in the clinker. Hence, to get the desired raw material proportions each of dw_i must be divided by the CRCF factor defined earlier. Also the solution dw_i should 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 content 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 PSVD is applied for solution. This set of four equations with three unknowns constitutes an overdetermined set of equations and PSVD method is a better candidate for its solution [5]. 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.

Until now all calculations are made for dry composition of the raw material 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

$$X_i = \frac{\text{Dry proportion}}{1 - (\text{percentage of } H_2O)_i/100}$$

The entire procedure described above is summarized in Appendix A.

If the stacker reclaimer, a machine that feeds lime stone 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, SiO_2, Al_2O_3 and Fe_2O_3, 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

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

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

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

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.

5. 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 DOS environment. The detailed hardware requirements for implementation of this control system on a real plant are listed in Appendix B. The user interface for this scheme consists of user data entry, on line trending, and history of the plant data screens. Amongst other features alarm display for faults, manual and auto mode of operation are included. This software package consists of mainly three modules, the communication, control algorithm and user interface. The results of this control method have been verified over an extended period of time in a 2500 tons per day (tpd) dry process cement plant situated at Jayanthipuram, Andhra Pradesh, India, which is commissioned by FL Smidth, Denmark.

Table 1

Composition of Available Raw Materials

Feeder No.	CaO percentage	SiO_2 percentage	Al_2O_3 percentage	Fe_2O_3 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

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 chemical composition of the materials are shown in Table 1. 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 $AM = 1.1$. For our test we have ignored the effect of coal ash and the moisture in the input raw material, so the value of the coal ash constant is made zero.

Table 2

Results of FLS QCX and IRMPC method

Time (p.m.)	FLS QCS-program				PSVD based IRMPC (*LSF* ignored)			
	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

Time (p.m.)	PSVD based IRMPC (All moduli)				PSVD based IRMPC (*AM* ignored)			
	F1	F2	F3	Total Matl.	F1	F2	F3	Total Matl.
	percentage			tons	percentage			tons
6	--	--	--	--	--	--	--	--
7	--	--	--	--	--	--	--	--
8	93.56	0.67	5.76	225	99.12	0.00	0.88	230
9	94.97	1.14	4.51	228	94.09	2.26	3.67	225
10	92.56	3.47	4.09	232	93.36	2.51	4.12	223
11	93.14	3.98	2.87	230	92.28	4.88	2.97	232
12	93.72	3.52	3.76	228	92.90	2.01	5.08	230

The data taken for the testing of this method are from the log book of Jayanthipuram cement plant on 8th March 1993, from 6 p.m. to 11 p.m. and the control actions by this method are given in Table 2. In this table $F1, F2$ and $F3$ represents three feeders. In this plant, the composition of the raw meal is controlled by a computer routine (FLS QCX program) developed by FLS. With this existing setup the end product, i.e., the quality of the clinker has been kept at the desired level. So, the results of FLS QCX program has been taken as a standard for IRMPC algorithm. The FLS QCX program has the facility for providing weighting factors to the moduli set points. The FLS QCX results shown in Table 2, are based on achieving *SM* set point by 100 percent and AM set point by 50 percent. But IRMPC has been based on achieving all the moduli set points by 100 percent. In Table 2, IRMPC results correspond to three different cases, i.e., with different weights to the moduli, *LSF*, *SM* and *AM*. In the first case the weights are 0 percent for *LSF*, and 100 percent for *SM* and *AM*; in the second case, 100 percent weights are assigned to all moduli; and in the third case 100 percent weights are assigned to *LSF* and *SM*, and 0 percent is assigned to *AM*. The IRMPC depends on two previous *SP* values to calculate the errors, and so, in Table 2 the control actions are given from 8 p.m. to 12 mid-night. 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.

The results given in Table 2 indicate that the moduli set points have been achieved within two consecutive hours only, giving rise to a shorter settling time. This signifies the potentiality of the proposed method. So this method keeps the blending silo average *LSF*, *SM* and *AM*, very close to the desired one almost all the time. Hence, smooth feeder adjustments are possible during the calculation of new raw material proportions. The results obtained for all moduli to be satisfied indicate that in the absence of stacker reclaimer, the proposed IRMPC method will also give the desired moduli set points, i.e., the desired quality of clinker without hampering the production. These results are consistent with many other similar runs.

6. Conclusion

This paper presents a novel raw mix proportion control system. 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 delays
- takes into account the limiting values for feeder capacity and control action
- takes into account the LOI of raw material and coal ash
- takes into account moisture in the raw material
- 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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Appendix A. IRMPC Algorithm

Step 1 BEGIN:

Find the maximum absorption of coal ash in clinker (on LOI free basis), which is

$$= (\text{percentage of ash in coal}) \times \frac{\text{Kiln Heat Consumption}}{\text{Calorific Value of Coal}} \times \\ \times (1 - \frac{\text{LOI of Coal Ash}}{100}).$$

Step 2 Calculate the chemical composition of the raw material on clinker basis.

Step 3 Find the intermediate Set Point(SP) values for each of the modules as per equation (12):

$$(Mod)_{ISP} = (Mod)_{\text{SP}} + \Delta(Mod)_{\text{SP}},$$

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

Step 4 Calculate the process dead time compensation value from the knowledge of the process characteristics.

Step 5 Compute the composition change as in equation (14):

$$\mathrm{d}Mod' = Mod_{\mathrm{SP}} - (Mod)_{\mathrm{Meas}} + DC + \Delta Mod_{\mathrm{SP}}.$$

Step 6 Calculate the elements of the differential coefficient matrix as in equation (20).

Step 7 Form the matrix $\boldsymbol{D}$.

Step 8 Compute the pseudoinverse of the matrix $\boldsymbol{D}$ by PSVD technique and then the solution for $\boldsymbol{dw}$ as in equation (22).

Step 9 Check for the constraints to be satisfied by $\boldsymbol{dw}$ as in equation (9). If satisfied, then go to STEP 12.

Step 10 Set the value of $\boldsymbol{dw}$ not satisfying the constraints in equation (9) to its limiting value and go to STEP 7.

Step 11 Convert the $\mathrm{d}W_i$ values to its raw meal equivalents.

Step 12 Convert the $\mathrm{d}W_i$ values to its equivalent wet proportions.

Step 13 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 7.

Step 14 Give the values of $\mathrm{d}w_i$.
END:

Appendix B. Hardware requirement for real time implementation

- Computer requirement

  One PC/AT-386 with a minimum of 640KB main memory, 20MB Hard Disk, 1.2 MB Floppy Disk Drive, and one 14" SVGA monitor, one serial port, two parallel ports.

- Printer

  One 24 pin Dot Matrix Printer.

- Uninterrupted Power Supplies

  One 0.5 KVA UPS

- Interface

  PLC and *RS*422.