Kovove Mater. 53 2015 377–383
DOI: 10.4149/km_2015_5_377

An experimental study of the effect of clinker hardness on ball mill output and mathematical modelling of operational parameters using RSM method

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Received 12 July 2014, received in revised form 1 December 2014, accepted 1 December 2014

Abstract

One of the operational parameters in ball mill grinding process of composite cement is clinker hardness (litre weight of clinker). The quantity of fly ash to be blended in the composite cement is highly dependent on the clinker hardness. In this paper, the Response Surface Methodology (RSM) is used to formulate the experimental design and to analyze the effect of the operational parameters (input factors) such as clinker feed rate in tonnes per hour, fly ash feed rate in tonnes per hour and litre weight of clinker (clinker hardness) in grams/litre. The responses reported were mill output in tonnes per hour, cement residue in percentage, three days compressive strength in kg cm^{-2}, 28 days compressive strength in kg cm^{-2}, initial setting time and final setting time in minutes. The analysis using RSM revealed that in general the clinker hardness significantly affected the mill output. Mathematical models were developed to predict the responses.

Key words: ball mill, fly ash, cement clinker, composite cement, response surface methodology

1. Introduction

Grinding processes are particularly energy consuming [1] in a cement industry since the energy consumption associated with grinding the raw materials and clinker in ball mills represents approximately 75 % of the cement production costs. A ball mill is the equipment used for grinding the hard, nodular *clinker* from the cement kiln into the fine grey powder. Most types of cement are produced using the Portland clinker and the ball mills are widely used for the grinding process of Portland clinker. A ball mill is a horizontal cylinder partly filled with steel balls (or occasionally other shapes) that rotates on its axis, imparting a tumbling and cascading action on the balls present inside the mill. Material fed through the mill is crushed by impact and ground by attrition between the balls, also called grinding media. The smaller grades of grinding media are occasionally cylindrical rather than spherical. There exists a speed of rotation at which the contents of the mill would ride over the roof of the mill due to centrifugal action.

Ball mill grinding systems of cement manufacturing are either open circuit or closed circuit system [2]. Figure 1 presents the design of the grinding system (closed circuit), consisting of a two-chamber ball mill and the separators. The output achieved by a ball mill system varies according to the mill power, the fineness of the product and the hardness of the clinker. The litre weight of clinker, which is indirectly a measure of the clinker hardness [3], is an important factor that impacts the energy cost of the grinding process and it depends both on the clinker's mineral composition and its thermal history. The performance optimization of the ball mills is very much essential and will be possible only if the operational parameters of the ball milling process are known.

Michael Boulvin, Alain Vande Wouwer presented a nonlinear distributed parameter model of a grinding circuit used in the cement industry and on the basis

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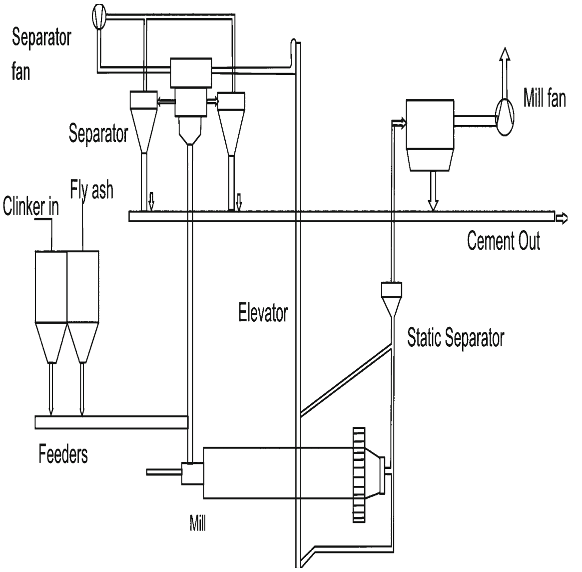

Fig. 1. Schematic layout of a ball mill grinding process of cement manufacturing.

of the experimental data collected on the real plant, a dynamic simulator was developed [1]. Hanifi Binici et al. [4] explored the capability of Genetic Expression Programming (GEP) in the prediction of heat of hydration of portland and blended cements. They have concluded that the proposed GEP models can be used as an important decision support mechanism to assist technicians in the prediction of heat of hydration of portland and blended cements. Cement Kiln Dust (CKD) produced in a cement production plant in Saudi Arabia along with fly ash resulting from combustion of heavy fuel oil in a local power generation plant were utilized by M. A. Daous [5] as waste material blends with portland cement, produced from the local plant, at various proportions. Bhatty [6] reported that due to the high lime content of CKD and subsequent ability to harden upon exposure to moisture, it is commonly used as a mixture with different solid-waste materials such as waste glass, fly ash, waste water sludge with the addition of cement [7]. The utilization of different classes of fly ash as a partial replacement of cement or aggregates in concrete mixes was investigated by many researchers in the last few years. It was reported that such utilization led to various technical, economical, and environmental benefits [8–10]. In this literature, it is seen that the study of the effect of clinker hardness on ball mill output and the mathematical modelling of operational parameters have not been attempted by the authors. Hence an initiative has been carried out in this research.

2. Methodology

The Response Surface Methodology (RSM) was developed for reducing the number of experimental trials needed to evaluate multiple parameters and their interactions.

Response Surface Methodology [11] is a collection of statistical and mathematical methods useful for the modelling and analyzing the engineering problems. In this technique, the main objective is to optimize the response surface influenced by various operational parameters. Response Surface Methodology also quantifies the relationship between the controllable input parameters and the obtained response surfaces. The design procedure of RSM is as follows:

(i) Designing a series of experiments for adequate and reliable measurement of the response of interest.

(ii) Developing a mathematical model of the second order response surface with the best fittings.

(iii) Finding the optimal set of experimental parameters that produce the maximum or the minimum value of response.

(iv) Representing the effects of operational parameters through two or three dimensional plots.

If all variables are assumed to be measurable, the response surface can be expressed as follows:

$$y = f(x_1, x_2, \dots x_k). \tag{1}$$

It is assumed that the independent variables are continuous and controllable by experiments with negligible errors.

3. Material and methods

Fly ash is an artificial pozzolanic material, which is an inorganic residue obtained from the burning of pulverized coal and has cementitious properties, when mixed with cement is referred as composite cement. As it comes under hazardous waste material, the disposal is also a major problem. Henceforth this fly ash is used as an additive for many products and one of these products is composite cement. Class F fly ash was selected for this study and grinding was carried out in a commercial ball mill with two chamber end discharge ball mill of size ø 4.2 m × 11.4 m.

The objective of this research is to utilize the historical data design based on RSM for selecting the optimum set of input factors in a ball mill grinding process. The input factors selected were clinker feed rate, fly ash feed rate, litre weight of clinker. The input factors and their levels are shown in Table 1. The responses recorded were mill output, cement residue, 3 days compressive strength, 28 days compressive strength, initial setting time and final setting time [12]. The desirable range of the responses as per IS standards is shown in Table 2.

Historical data design based on RSM with 27 experimental runs [13] was chosen and the working

Table 1. Desirable range of input factors and levels

Sl. No.	Input factors	Range	Units	Levels 1	Levels 2	Levels 3
1	Clinker feed rate, C	52–60	tph	52	56	60
2	Fly ash feed rate, A	16–24	tph	16	20	24
3	Litre weight of clinker, W	1200–1400	g l^{-1}	1200	1300	1400

Table 2. Desirable range of responses

Sl. No.	Responses	Range
1	Mill output, O	80–88 tph
2	Residue (fineness), R	2–6 %
3	3 days compressive strength, $S1$	230–260 kg cm^{-2} or 23–26 MPa
4	28 days compressive strength, $S2$	430–460 kg cm^{-2} or 43–46 MPa
5	Initial setting time, $T1$	Initial $\geq$ 60 min
6	Final setting time, $T2$	Final $\leq$ 600 min

Table 3. Design matrix and the responses

	Input Factors			Responses					
Sl. No.	Level of C	Level of A	Level of W	O (tph)	R (%)	$S1$ (kg cm^{-2})	$S2$ (kg cm^{-2})	$T1$ (min)	$T2$ (min)
1	3	2	3	74	9.8	330	370	260	370
2	1	1	2	72	3.2	270	640	200	285
3	2	3	3	72	9.6	315	330	185	330
4	1	1	3	72	9.8	335	385	285	375
5	3	1	2	80	3.4	275	630	255	330
6	1	2	1	76	2.2	175	400	130	250
7	2	2	2	80	3.2	270	640	175	260
8	1	3	1	80	1.8	170	390	100	235
9	3	1	1	80	2.6	200	440	215	285
10	2	1	3	73	9.8	340	380	305	385
11	3	3	2	88	2.6	255	595	165	275
12	2	2	1	80	2.2	180	410	155	255
13	2	3	1	84	2.2	175	380	105	240
14	1	3	2	80	2.4	245	590	150	265
15	1	2	2	76	3.2	260	605	170	270
16	2	2	3	73	9.6	325	370	245	255
17	3	3	1	88	2.2	175	395	115	245
18	1	1	1	72	2.4	190	425	175	270
19	2	1	2	76	3.4	275	635	215	300
20	2	3	2	84	2.8	250	590	155	265
21	1	2	3	73	9.4	320	365	220	345
22	1	3	3	75	9.2	315	340	285	375
23	3	2	2	84	3.2	265	610	195	280
24	3	2	1	84	2.4	185	415	160	265
25	2	1	1	76	2.2	190	430	200	280
26	3	3	3	74	9.4	320	350	195	340
27	3	1	3	74	10.2	345	390	335	400

ranges of the parameters were set at three levels.

Experiments were conducted according to the experimental design matrix using a pilot laboratory ball mill of size ø 500 × 480 mm^2 with an addition of a constant amount of 5 % gypsum to increase the setting time. For each trial run the pilot mill was run for 40

Table 4. R-squared values of responses

R-squared value					
O	R	$S1$	$S2$	$T1$	$T2$
0.95120614	0.99835741	0.998438122	0.996159241	0.933888878	0.868144828

Table 5. P-values for O, R, $S1$, $S2$, $T1$, and $T2$

Source	O	R	$S1$	$S2$	$T1$	$T2$
	Prob > F	Prob > F	Prob > F	Prob > F	Prob > F	Prob > F
Model	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
A	< 0.0001	0.0072	< 0.0001	0.1524	0.0423	0.2247
B	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	0.0024
C	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
A^2	0.5604	0.6371	0.6554	0.9382	0.3728	0.0692
B^2	1.0000	0.3501	0.3763	0.3991	0.1398	0.0341
C^2	< 0.0001	< 0.0001	< 0.0001	< 0.0001	0.0434	0.0162
AB	0.5372	1.0000	0.6361	0.7427	0.0071	0.2157
AC	0.0002	0.7383	1.0000	0.6232	0.2213	0.7518
BC	0.0002	0.3225	0.3487	0.8695	0.8830	1.0000

min duration and a total of 27 trial runs were carried out. A cube moulding machine was used to produce 54 cube samples of size 7.07 × 7.07 × 7.07 cm^3 and the compressive strength was tested for 3 and 28 days cubes using compression testing machine. The fineness of cement was tested using the sieve analyzer. Initial and final setting time was measured by using the VICAT apparatus. The mill output was measured by electronic weighers. The design matrix and the responses are shown in Table 3.

4. Regression analysis and mathematical model

The response function representing any of the process parameters can be expressed as:
$Y = F(C, A, W)$, the relationship selected being a second degree response surface is expressed as follows:

$$Y = b_0 + b_1 C + b_2 A + b_3 W + b_{11} C^2 + b_{22} A^2 + b_{33} W^2 + b_{12} CA + b_{13} CW + b_{23} AW, \quad (2)$$

where C is clinker feed rate (tph), A is fly ash feed rate in (tph), and W is litre weight of clinker (g l^{-1}).

Any mathematical model developed should be studied for both its direct and interaction effects of the variables on the responses. To determine the significant direct and interaction effects precisely, a statistical analysis software package, namely Design Expert 6.0.8 was used. The general mathematical model for the factors (based on ANOVA) was analyzed and the models [14] having the significant direct and interaction effects only with calculated regression coefficients are as follows:

$$O = -898.00000 + 4.63194C + 7.52778A + 1.18167W + 0.020833C^2 - 3.33333 \times 10^{-4}W^2 - 0.015625CA - 4.58333 \times 10^{-3}CW - 4.58333 \times 10^{-3}AW, \quad (3)$$

$$R = 436.31667 + 0.20972C + 0.26250A - 0.71683W - 2.08333 \times 10^{-3}C^2 - 4.16667 \times 10^{-3}A^2 + 2.90000 \times 10^{-4}W^2 + 4.16667 \times 10^{-5}CW - 1.25000 \times 10^{-4}AW, \quad (4)$$

$$S1 = -2204.81481 + 5.38194C - 1.38889A + 2.86111W - 0.034722C^2 + 0.069444A^2 - 8.05556 \times 10^{-4}W^2 - 0.026042CA - 2.08333 \times 10^{-3}AW, \quad (5)$$

$$S2 = -37783.28704 + 1.84028C + 0.59028A + 59.26528W + 0.017361C^2 - 0.19097A^2 - 0.022806W^2 + 0.052083CA - 3.12500 \times 10^{-3}CW - 1.04167 \times 10^{-3}AW,$$

$$T1 = 1743.98148 - 3.68056C + 16.38889A - 2.99444W + 0.45139C^2 + 0.76389A^2 + 1.72222 \times 10^{-3}W^2 - 1.06771CA - 0.017708 \times 10^{-3}CW + 2.08333 \times 10^{-3}AW, \quad (6)$$

$$T2 = 6823.24074 - 105.59028C - 28.33333A - 5.59167W + 1.11111C^2 + 1.31944A^2 + 2.44444 \times 10^{-3}W^2 - 0.52083CA - 5.20833 \times 10^{-3}CW. \quad (7)$$

The model adequacy was examined through resid-

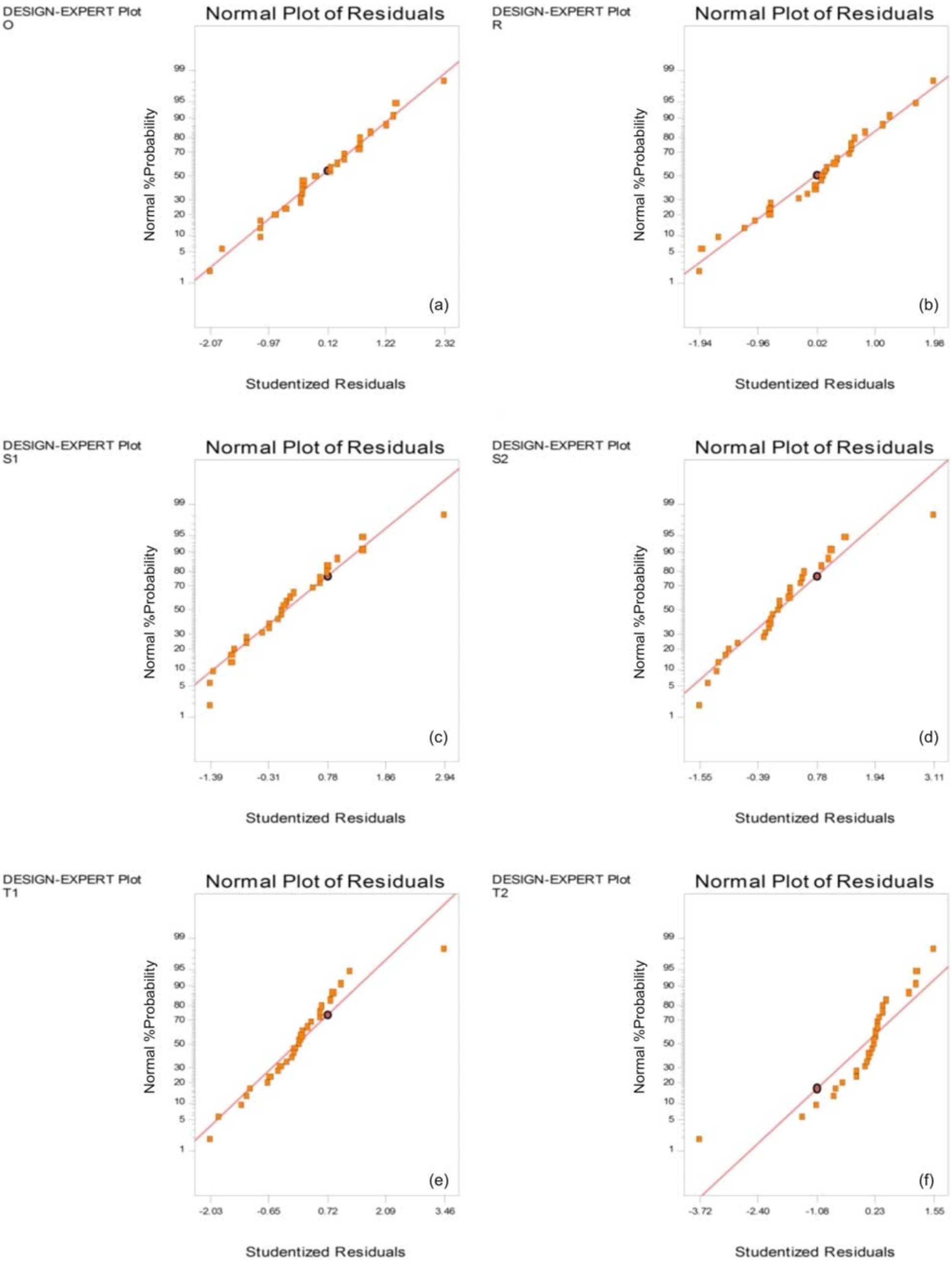

Fig. 2a–f. Normal probability plots of residuals.

Table 6. Optimal solution of RSM

C	A	W	O	R	$S1$	$S2$	$T1$	$T2$
56.33	24	1301.33	82.6975	2.8369	253.647	591.832	145.546	258.023

Table 7. Software predicted responses and actual experimental results

	O	R	$S1$	$S2$	$T1$	$T2$
Predicted responses by software	82.6975	2.8369	253.647	591.832	145.546	258.023
Actual experimental value	80	2.6	250	595	141	260

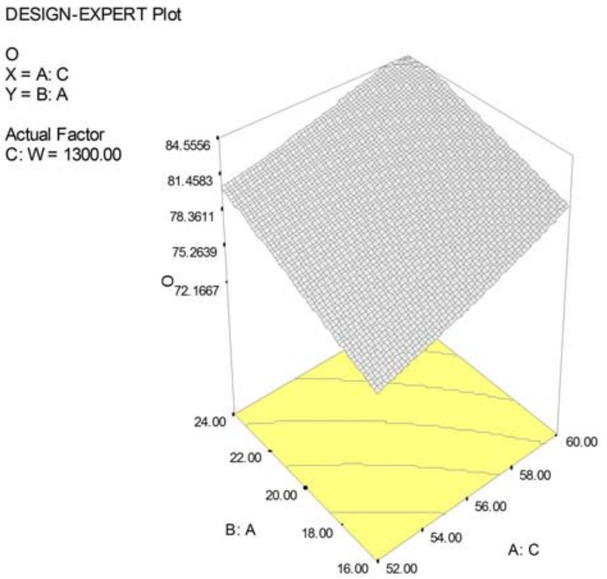

Fig. 3. Main and interaction effects of clinker feed rate, fly ash feed rate on mill output

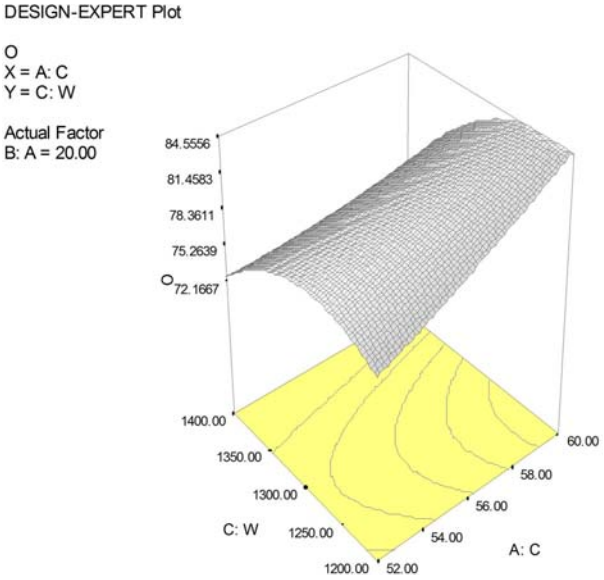

Fig. 4. Main and interaction effects of clinker feed rate, litre weight of clinker (clinker hardness) on mill output.

ual analysis. Figures 2a–f show the normal probability plots of the residuals indicating that the responses are legitimate.

An analysis of variance (ANOVA) was used to calculate the regression coefficients and to check the significance of the models developed. Table 4 shows the R-squared values of the responses. The P-values of the responses are shown in Table 5 and the optimal solution of the RSM is shown in Table 6.

5. Confirmation experiments

Confirmation experiments were conducted at the optimal settings of the operational parameters and the results obtained from the experiments were compared with the predicted responses as shown in Table 7. The experimental responses were found to be significantly close to the predicted responses, confirming the adequacy.

6. Results and discussion

Figures 3–5 show the main effects and the interaction effects of clinker feed rate, fly ash feed rate and litre weight of clinker on mill output.

Figure 3 shows that the mill output increases with the increase in clinker and fly ash feed rate. This is due to the fact that grindability of the mill is not affected by the feed rate within the experimental region.

Figure 4 shows that the mill output increases with the increase of clinker feed rate and litre weight of clinker whereas it decreases with further increase in clinker feed rate and litre weight of clinker. Thus, it is evident that the output of the mill suffers due to the increase in clinker hardness.

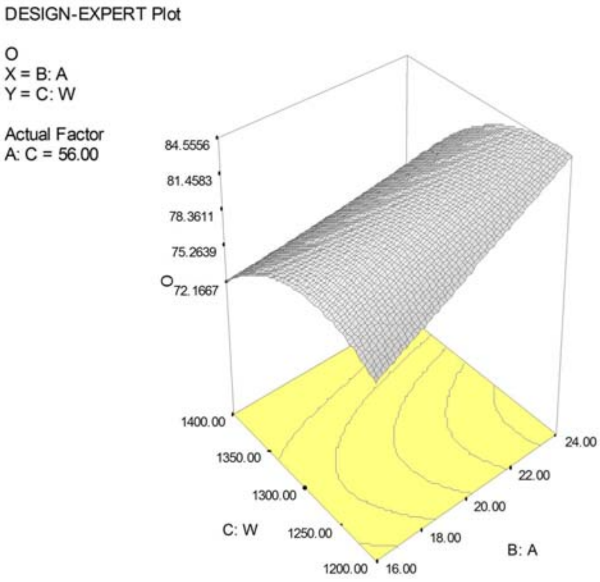

Fig. 5. Main and interaction effects of fly ash feed rate, litre weight of clinker (clinker hardness) on mill output.

Figure 5 shows that the mill output increases with the increase of fly ash feed rate and litre weight of clinker whereas it decreases with further increase in fly feed rate and litre weight of clinker. This is also due to the increase in litre weight of clinker which is an indicator of clinker hardness.

7. Conclusions

The following conclusions are derived from this experimental research work:

1. The effect of clinker hardness on the mill output was investigated and RSM technique was adopted to optimize the addition of fly ash and the litre weight of clinker in ball mill cement grinding process.

2. The optimum value for the litre weight of clinker was found to be 1301.33 g l^{-1}. Above this the 28 day compressive strength and the mill output decreases.

3. The optimum value for addition of fly ash was found to be 24 tph. Above this the compressive strength of cement decreases.

4. This research work would be useful in increasing the productivity of the ball mill in cement industry and would aid in conservation of limestone resources. The models can be used as a quick decision making tool in cement industry for predicting the responses.

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