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Pelletization of iron ore fines with parameter optimization through box-behnken design

Abstract

Present study is focused on optimization of process parameters during green Pelletization to ascertain the significance of green pellet in indurations. Three levels Box-Behnken design in combination with Response Surface Methodology (RSM) was used for modelling and optimization of parameters like d50 yield of +9mm pellets, MDN and GCS of pellets. Beneficiation studies were carried out and the optimum condition obtained for good strength green pellets are at d50 of 13.8mm, % yield of +9mm pellets of 93.29%, MDN of 17.3 and GCS of 1.94kg/pellet were obtained at the moisture (M) of 14 %, rotation (R) of 44.39rpm and betonies (B) of 0.54 wt.

Keywords: Green Pelletization; Box-Behnken Design; RSM; Modeling and optimization.

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Introduction

Iron and Steel industry is considered the backbone of industrial development. The mining of iron ore has a prime importance among all the minerals mined in our country.[1,2] In recent years, Government of India (GoI) has stipulated a rule to use iron ore up to 45% Fe not to dump fines and slimes as waste, so to conserve the limited reserves of good quality and to increase the usage of low grade ore in the blast furnace feed mix. With the increase in mechanized mining activity and the soft and friable nature of the ores, the generation of fines and ultra-fines has been steadily increasing.[3–5] In addition to this, the steps involved in beneficiation process, handling and transportation operation generate fines and ultra-fines. These fines and ultra-fines can be efficiently used for the production of iron and steel, if used in the form of pellets or sinters, either directly or after beneficiation.[3] The main raw material in iron-steel industry is iron ore which can be classified as high grade and low grade in terms of their Fe content.[6,7]

The most commonly employed agglomeration technique is pelletizing, wherein a mixture of iron ore, water and binder is rolled in a mechanical disc or drum to produce agglomerates (green balls or wet pellets).[7–9] The green pellet quality significantly affects the fired pellet quality. Bentonite is the most commonly used binder in iron ore Pelletization. It not only controls the moisture in iron concentrate but also remarkably improves physical properties of the pellets. However, there are some major drawbacks with the use of betonies. The most striking is the contamination of the product with gangue (silica). Addition of 1% betonies to an iron ore concentrate results in a lowering of acid pellet iron content by 0.6%. In case of direct reduction pellets, every percent of acid gangue addition is associated with an increased energy consumption of 30 kWh.[10] Many researchers attempted to find suitable pellet production systems to achieve production of stronger pellets using either alternate binders or new methods against the conventional ones.[11]The iron ore pellets produced through Pelletization operations are used in the Blast Furnace (BF) for production of iron and in DRI for sponge iron production.[12,13]

The parameters which affect the Pelletization process are moisture content, drum or disc inclination, fineness of feed, speed of drum or disc, Pelletization time, type and viscosity of binders, etc.[9,12,14,15] The most important iron ore Pelletization parameters that affect the agglomeration are wetting-nucleation, consolidation-growth and attrition-breakage.[16–18]

This paper outlines the statistical analysis of the influence of process variables on the green pellet characteristics of Barsua iron ore fines.

Experimental

Material preparation

The size analysis results indicate that the d80 and d50 passing sizes of the sample are 1900µm and 150µm respectively. The Fe content is more in finer sizes with lesser silica and alumina contents. The -150µm size fraction of about 51% contains 61% Fe.

The -3mesh ROM iron ore sample, collected from Barsua iron ore mines of Odisha, was crushed in a dodge type jaw crusher. The crushed product was passed through a roll crusher, which was then ground to 100% passing 200mesh in a ball mill. This head sample was used for characterization. Beneficiation studies were carried out after grinding the sample to -150µm using Wet High Intensity Magnetic Separation (WHIMS) to obtain pellet grade concentrate. The sample prepared for the Pelletization study contains approximately 85% below 350mesh.

Experimental setup

Pelletization experiments were carried out on a disc pelletizer having a diameter of 40cm and a rim height of 15cm. The disc is driven by a 1hp engine through reduction gears and provided with a variable speed drive mechanism to regulate the disc speed. The disc is provided with a facility to change the disc inclination. Iron ore sample of 1kg each was mixed with betonies at different proportions prior to the Pelletization study. Moisture was added slowly and continuously. Pelletization time and disc inclination were fixed at 20min and 42°, after preliminary studies. The quality of pellets was tested for size analysis (d50), % yield of +9mm pellets, mean drop number (MDN) and green compressive strength (GCS).

Design of experiments (DOE)

Box-Behnken design of experiments are considered better over full factorial design in that the same output information can be obtained with less number of experiments. Box-Behnken design was used in the present study and the product pellet characteristics of d50, yield of +9mm pellets, MDN and GCS were analyzed as functions of the design and operation parameters.

A full factorial design of three variables with three levels i.e. 33, will involve a total of 27 experiments, it consume more time and material for all the experiments. Box-Behnken Design was used which includes only 15 tests to give all the prediction as given by conventional factorial design. The designs of experiments with experimental data are presented in Table 1, and their levels are shown in Table 2. It is being commonly used to determine the main and interactional effects among two or more factors of the process variables.[19–23] Design of experiments conducted for experimental data has been made by Minitab 17 (Trial).

Table 1 Experimental results along with the operating variables

Test no.	Variables			Responses			
	Actual and coded levels of variables			Observed result			
	X1	X2	X3	d50	%Yield	MDN	GCS
1	-1	-1	0	9.47	70.2	5.2	1.07
2	1	-1	0	13.5	97.6	8.62	1.51
3	-1	1	0	10.6	80.3	6.68	1.08
4	1	1	0	14.12	94	17.29	1.84
5	-1	0	-1	9.4	72.8	5.01	0.85
6	1	0	-1	13.83	95.1	9.66	1.2
7	-1	0	1	10.86	81.5	7.33	1.21
8	1	0	1	13.7	99.2	17.38	2.18
9	0	-1	-1	11.41	95.7	5.45	1.03
12	0	1	1	13.08	98.8	13.98	1.91
13	0	0	0	10.5	88	9.8	1.87
14	0	0	0	10.5	88	9.8	1.87
15	0	0	0	10.5	88	9.8	1.87

Table 2 Level of the variables considered

Variables	Symbols	Coded Variable Levels		
		Low	Medium	High
		-1	0	1
Moisture (%)	X1	10	12	14
Disc speed (rpm)	X2	35	40	45
Bentonite (Wt. %)	X3	0.25	0.5	0.75

RSM was used to generate the relationship between dependent and independent variables. A quadratic response surface design comprises of both polynomial and factorial regression equations. The general regression equation for three variables X1, X2and X3are given below;

$$y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_1^2 + \beta_5 X_2^2 + \beta_6 X_3^2 + \beta_7 X_1 X_2 + \beta_8 X_1 X_3 + \beta_9 X_2 X_3 \quad (1)$$

Where, y is the predicted response, β is model constant; X_1, X_2 and X_3 are independent variables; β_1, β_2 and β_3 are the linear coefficients; β_4, β_5 and β_6 are the quadratic coefficients and β_7, β_8 and β_9 are the cross product coefficients.[23]

Results and discussion

Analysis with design of experiments

The results obtained from the experiments were plotted to obtain d50 values at different operating parameters. The proportion of pellets above 9mm (% yield of +9mm pellets), the strength parameters i.e. MDN and GCS were calculated. The results were used to develop correlations between the input and output parameters (Eq. 2-5).

$$d_{50} = 63.06 - 1.361X_1 - 2.5823X_2 - 1.75X_3 + 0.1331X_1^2 + 0.0356X_2^2 + 14.64X_3^2 - 0.01275X_1X_2 - 0.795X_1X_3 . \quad (2)$$

$$\boldsymbol{\%\ Yield} = -122.7 + 53.74X_1 - 81.0X_3 - 1.409X_1^2 + +0.1265X_2^2 + 76.6X_3^2 - 0.3425X_1X_2a \quad (3)$$

$$\boldsymbol{MDN} = 49.7 - 6.45X_1 - 0.804X_2 - 27.9X_3 + 0.179X_1X_2 + 2.7X_1X_3 . \quad (4)$$

$$\boldsymbol{GCS} = -19.65 + 1.670X_1 + 0.4653X_2 + 2.415X_3 - 0.08281X_1^2 - 0.00655X_2^2 - 2.860X_3^2 + 0.008X_1X_2 + 0.31X_1X_3 - 0.046X_2X_3 . \quad (5)$$

In all the equations, the term with positive and negative sign indicate the positive and deleterious influence of the parameters. This statement is also evidenced from the Fisher test value (F-value) for the model which gives the level of significance of the different parameters. Larger the F-value more is the significance. The significance of the variables can also be determined by Probability Test (P-value/ Significance Probability Values). A P-value is the probability of an observed result assuming that the null hypothesis is true. The term is considered as highly significant if the P-value is below 0.01. The term is significant and acceptable if the p-value is below 0.05.[24–26] The ANOVA was prepared for all the four response models and the results of ANOVA and the main and interactional effects for the green pellet parameters are presented in Tables 3 and Table 4. The correlation between the observed and predicted values shows that the fit is quite good with an R2 value of 0.9996 for d50, 0.9909 for yield of +9mm pellets, 0.9943 for MDN and 0.9969 for GCS.

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Table 3 ANOVA table

Variables	d_{50}				%Yield			
	SS	MSS	F-Value	P-Value	SS	MSS	F-Value	P-Value
Moisture	27.454	27.454	8785.3	0	822.15	822.15	377.74	0
Rotation	1.575	1.575	504.1	0	4.96	4.96	2.28	0.191
Bentonite	1.03	1.03	329.48	0	46.08	46.08	21.17	0.006
Moisture*Moisture	0.608	1.047	335.03	0	143.76	117.35	53.92	0.001
Rotation*Rotation	2.495	2.925	935.9	0	29	36.93	16.97	0.009
Bentonite*Bentonite	3.091	3.091	989.21	0	84.63	84.63	38.88	0.002
Moisture*Rotation	0.065	0.065	20.81	0.006	46.92	46.92	21.56	0.006
Moisture*Bentonite	0.632	0.632	202.25	0	5.29	5.29	2.43	0.18
Rotation*Bentonite	0.014	0.014	4.61	0.085	6.76	6.76	3.11	0.138
Variables	**MDN**				**GCS**			
	SS	MSS	F-Value	P-Value	SS	MSS	F-Value	P-Value
Moisture	103.177	103.177	422.95	0	0.794	0.794	507.22	0
Rotation	37.195	37.195	152.47	0	0.041	0.041	25.95	0.004
Bentonite	50	50	204.96	0	1.03	1.03	657.9	0
Moisture*Moisture	0.004	0.009	0.04	0.857	0.351	0.405	258.88	0
Rotation*Rotation	0.359	0.341	1.4	0.29	0.084	0.099	63.26	0.001
Bentonite*Bentonite	0.032	0.032	0.13	0.73	0.118	0.118	75.38	0
Moisture*Rotation	12.924	12.924	52.98	0.001	0.026	0.026	16.36	0.01
Moisture*Bentonite	7.29	7.29	29.88	0.003	0.096	0.096	61.41	0.001
Rotation*Bentonite	0.063	0.063	0.26	0.634	0.013	0.013	8.45	0.034

Table 4 Represents the main and interactional effect of the green pellet parameters

Response	Main effect	Interactional effect
d_{50}	M > R > B	M × B > M × R > R × B
% Yield of +9 mm pellets	M > B > R	M × R > R × B >M × B
MDN	M > B > R	M × R >M × B > R × B
GCS	M > B > R	M × B > M × R > R × B
Where, M = Moisture content, R = Disc Speed and B = Binder content		

Effects of variables

In order to gain a clear understanding of the interactional effects of all the variables on the four responses viz. d50, % yield of +9mm pellets, MDN and GCS. 3D plots for all the responses were drawn, to evaluate the relationship between dependent and independent variables. Since the model has more than two factors, one factor was held constant at central level for each plot, leading to a total of twelve response surface plots.

On d50 and % yield

Figure 1a & Figure 2a show the 3D response surface relationship between M and R on d50 and % yield of +9mm pellets at centre level of B i.e. 0.5%. An increase in d50 and % yield of +9mm pellets was noticed with increase in M and R. As moisture acts as a natural binding agent due to its surface tension, particles come closer and aggregate together. The pellet size increases with increase in M with corresponding increase in d50. It was also observed that d50 of the pellet slightly increased and %yield of +9mm pellets slightly decreased with increase in R. The increase in R makes the pellets strike with great force at the rim of pelletizer which results in breakage of pellets. The layering of the broken fragments might not have happened within the total time of pelletization. Hence, although the d50 had increased, the % yield of +9mm pellets didn't show any increase.

Figure 1b and Future 2b show the 3D response surface relationship between M and B on d_{50} and %yield of+9mm pellets at centre level of R i.e. 40rpm. The maximum d_{50} and %yield of +9mm pellets were obtained at higher M and B. This is due to the strong mobile liquid bridging of particles. It is known that Bentonite uses moisture equivalent to its quantity to swell and provide more sites for the bonding of particles.

The 3D response surface relationship between R and B on d_{50} and %yield of +9mm pellets at centre level of moisture M i.e. 12%, are given in Figure 1c & Figure 2c. It is seen that initially the d_{50} decreased and then increased with increase in B. The increase in d_{50} was marginal but the decrease in % yield of +9mm pellets was steep with increase in R. At higher R, the pellets break due to high impact with the rim of pelletizer and also due to collision among themselves. Because of continuous breaking of pellet, the layering of broken fragments on surviving pellets may not have occurred. Increase in R leads to higher centrifugal force and hence pellet growth is constrained and retarded.

On mean drop number

Figure 3a shows the 3D response surface relationship between M and R on MDN of green pellet at centre level of B i.e. 0.5%. Figure 3b shows the 3D response surface relationship between M and B on mean MDN of green pellet at centre level of R i.e. 40rpm and Fig 3c shows the 3D response surface relationship between R and B on mean MDN of green pellet at centre level of M i.e. 12%.

Maximum drop number was noted at higher M, R and B. This may be attributed to the combined effect of increased M availability, enhanced M–B interaction and regular creation of new sites due to crushing and layering enabling moisture bridging of the particles and stronger cohesive bonding.

On green compressive strength

Figure 4a shows the 3D response surface relationship between M and R on GCS of green pellet at centre level of B, i.e. 0.5%. The GCS was found to be increasing when R increase. In case of M, it increased up to a certain point i.e. 12%, after which it was decreasing gradually. This may be due to increase in M at higher level of B leads to higher plasticity and made pellets of lesser GCS.

Figure 4b and Figure 4c show the 3D response surface relationship between M and B on GCS of green pellet at centre level of R i.e. 40rpm and the 3D response surface relationship between R and B on GCS of green pellet at centre level of M i.e. 12%, respectively. Moisture gives strength to the green pellet, but more moisture may lead to bigger pellets and lesser packing/bonding, thus showing decreased compressive strength. Similar trend was found for R. High dosage of B gives better compressive strength to green ball, as at higher B leads to greater solid-liquid and solid-solid bonding (Figure 4b & Figure 4c).

The predicted values and the actual data points indicated a good fit (R^2 value of 0.9996 for d_{50}, R^2 value of 0.9909 for % yield of +9mm pellets, R^2 value of 0.9943 for MDN and R^2 value of 0.9969 for GCS) of the response equations. This is shown graphically in Figure 5.

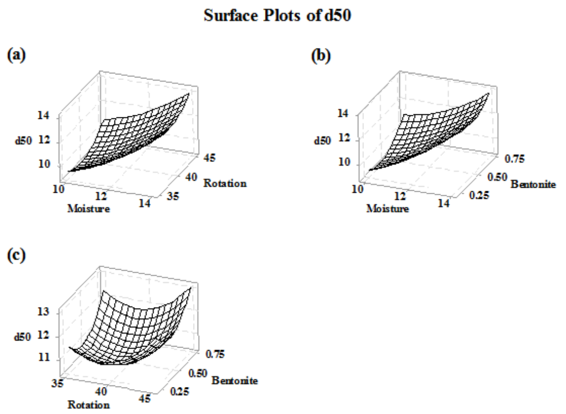

Figure 1 Effect of variables on d_{50}

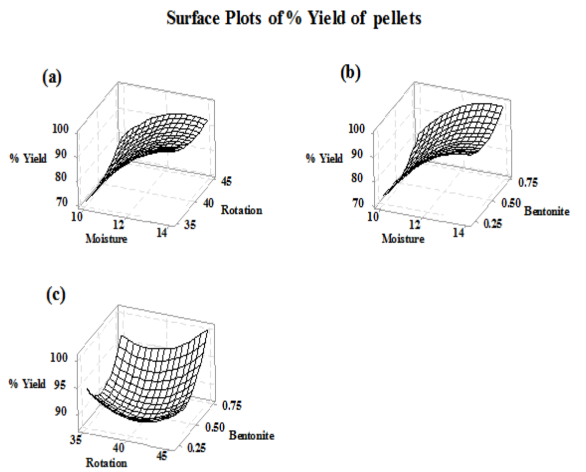

Figure 2 Effect of variables on yield of +9 mm pellet

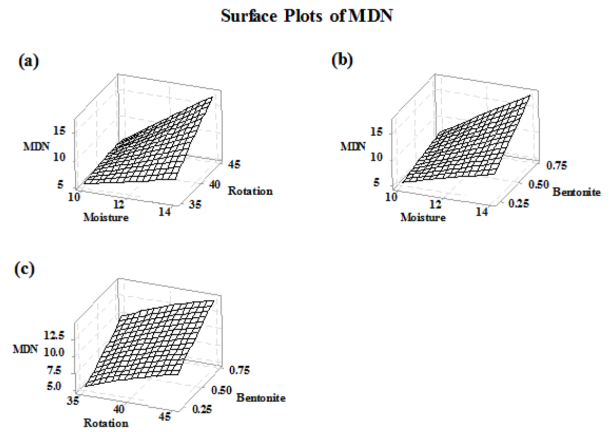

Figure 3 Effect of variables on MDN

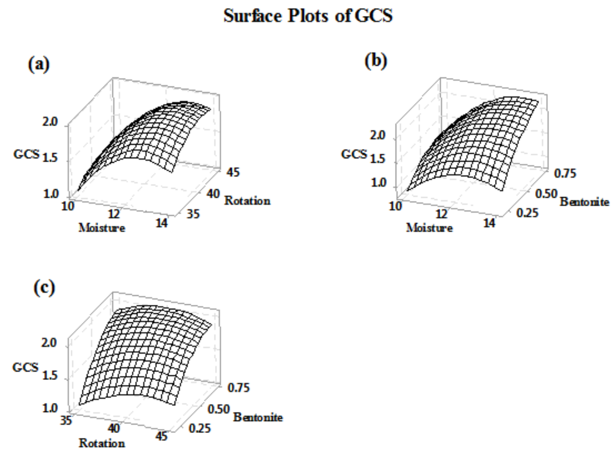

Figure 4 Effect of variables on GCS

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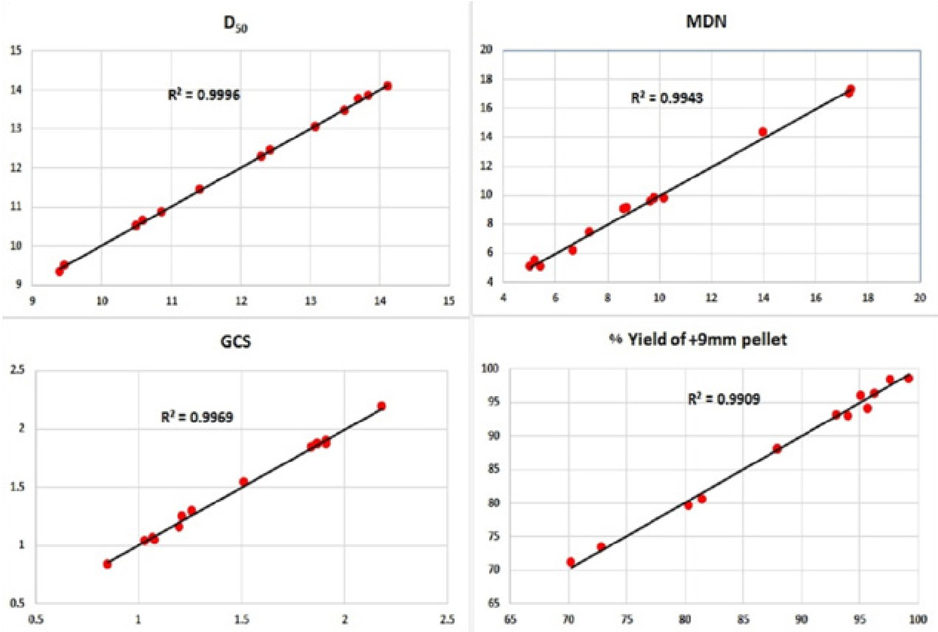

Figure 5 Relationship between actual and predicted values d50, MDN, GCS and % yield of +9mm pellets

Optimization

In iron ore green pelletization d_{50}, % yield of +9mm pellets, MDN, and GCS are the important parameters. The model equations were optimized using MINITAB Trial for evaluation of pelletization parameters on the targeted quality and quantity of the final product. The level considered for all these variables are mentioned in Table 2. However, optimization of each response is done individually (Table 5). Further, the variables were optimized to achieve the product of targeted quality. A yield of +9mm pellets was targeted at a minimum of 85% (Minimum of 85% of pellets required in the size range of +9mm to -18mm for blast furnace) among all the parameters and the optimized variables were derived. The parameters at which the best results were obtained are presented in Table 6.

Table 5 Individual optimization of response

Pellet Characteristics	Moisture, %	Disc speed, RPM	Bentonite, %	Maximum values of responses
d_{50}	14	45	0.25	15.1mm
% Yield	13.83	43.37	0.75	99.41%
MDN	14	45	0.75	21.06
GCS	13.47	41.06	0.75	2.22kg/ pellet

Table 6 Optimization of responses with targeted variables

Target M = 14%, R = 44.39 rpm, B = 0.54%	
d_{50}	13.8mm
% Yield of +9mm pellets	93.29%
MDN	17.3
GCS	1.94kg/pellet

Conclusion

In this study, a three-level Box–Behnken factorial design combined with a RSM was used for modelling and optimizing three operations parameters of the iron ore green pelletization. The mathematical model equations were derived for all the responses separately by using sets of experimental data and a mathematical software package (MINITAB 17 Trial).

It was found that best result of d50 of 13.8mm, % yield of +9mm pellets of 93.29%, MDN of 17.3 and GCS of 1.94kg/pellet were obtained at the M of 14 %, R of 44.39 rpm and B of 0.54 wt. %.

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Conflict of Interest

There is no conflict of interest in this work.

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