Optimization of Binder for Improving Strength and Shatter Index of Briquettes for BOF Dust using Design of Experiments

Ela Jha, S. K. Dutta

Abstract*: Effectiveness of Recycling of steel plant waste is very much dependent on agglomeration technique. Sintering, pelletization and briquetting are some of the techniques which are frequently used for waste utilization. Aim of this study is to prepare composite briquettes by cold bonding technique, by which phsico-chemical changesoccurred at room temperature or low temperature. Two binders are mixed in proportion to achieve the required properties specifically strength and shatter index. The design of experiments is used to find the proper combination of binders to get the optimum value of properties. Experimental work for the same is carried out in such a way that minimum number of experiment can give output as desired. For this 'Design of Experiment' methodology is applied to select the runs of experiment. After the selection of orthogonal array and experiment combinations, Taguchi technique is used with two variable (starch and molasses) and three levels (2.5%, 5% and 7.5% of each) i.e. L9 Array to analyze the results. Minitab15 software is used. Conclusion and comments are based on the same.

***Keywords* : Binders, Briquetting, Composite pellets/briquettes, Steel-plant wastes, Taguchi parametric design**

I. INTRODUCTION

Steel is the main driving force of economic progress in a country. The steel industry in India is poised to take a huge jump in production of the steel from 101.4 million tonnes (Mt) in 2017 to about 300 Mt by 2030. This target production compels the researchers to think a production level which is either zero waste or recycling of waste. The reserves of natural resources is the basic criteria which decides the development of any country. About 173Mtpa of processed iron ore and 215 Mtpa run of mine iron ore is needed for production of 101 Mtpa finished steel. India is fortunate to have reserves of high grade iron ores. But with time these reserves of high grade iron ores are bound to be diluted.

In a steel industry several processes are employed which uses various raw materials and in-process materials. At the same time many valueless substances are generated which are termed as waste materials. The waste can be categorized in terms of solid, liquid and gases. The solid wastes are from process units and also from pollution control units. The process wastes are generally utilized; the dust and sludge from pollution control unit is the area of attention. The aspect of waste management at various levels from mines to smelters is the attention of technocrats, mineral economists, planners and the consumers. The utilization of wastes is the area which need to be dealt with in a judicious and sustainable manner. Solid wastes generated from process units are generally characterized by their uniform size and composition. Low moisture content, high levels of metallic and non-metallic values (e.g. CaO, C etc.) content in wastes, which makes these suitable for recycling within the plant or to be sold out to consuming industries.

Efforts are being made to utilize the waste materials by proper characterization, beneficiation and agglomeration techniques[1-3]. The treatment of blast furnace sludge/dusts is the unsolved problem in many countries of the world[4,5]. Effective utilization of dust and sludge for iron and steel making can be possible after upgradation of Fe percent. There is a problem of coking coal : an important ingredient for steel making, throughout the world . Enormous amount of coal fines and coke breezes are also generated during coal mining and coking of coal respectively[6]. By incorporating non-coking coal fines with up-gradated dust and sludge in cold bonded iron oxide-coal composite pellets, the metallurgical coke requirement in the blast furnaces can be reduced and good quality pellets can be produced. Agglomeration of iron ore is a wet process, where particles are held together by the surface tension and capillary forces in wet condition. After drying the strength is provided by use of binders. Most widely used binder is bentonite clay (ideally Sodium Montmorillonite), Mandal and Sinha used only flux with iron ore fines and eliminated binder but need to harden the pellet at higher temperature[7,8].

Binder is an important part of any type of pellet especially in cold bonded iron oxide-coal composite pellets. The properties of pellet is evaluated in terms of strength and shatter index is greatly affected by the type of binder used for pellet making. Bentonite is the most used binder due to favorable mechanical and metallurgical pellet properties, but it contains impurities especially silica and alumina[9]. The U.S. Bureau of Mines investigated the use of organic binders as substitutes for bentonite in agglomerating iron ore concentrate. Over 30 organic binders were evaluated at several dosage levels in laboratory tests.[10]. Sah and Dutta[6] used binders such as

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lactose monohydrate, hemicellulose & sodium lignosulfonateand reported up to 300N/pellet strength from indurated pellets.Organic binders are desired when making low-silica iron ore pellets. Corn and wheat are grown in large quantities near certain iron ore pelletizing facilities and their starches are easily modified to form cold-water-soluble powders that can be used as binders[12]. Starch gives good dry pellets but strength and friability was found very poor as compared to bentonite.

Sah, Rahmadan& Dutta prepared pellets by cold bonding using various binders such as lime, Ca(OH)2, slaked lime, dextrose, molasses, and sodium polyacrylate (SPA), alone or in combination and more than 300N/pellet was observed[6]. Babuet all used molasses binder to prepare pellet with iron ore and good strength was noted.

The BOF dust used in this work is first beneficiated and Fe(T) is increased up to 62%. There are many binders available to be used for making cold bonded composite pellet. Out of several binders, the trial experiments are done; starch and molasses are selected for final experiments. The basis of selection is presented elsewhere[9]. Mixing two binders give the suitable properties to the pellets/briquettes. Mixing the two binders in any proportion is the trend followed till now and no logical method is used. There are many combination of binders gave compressive strength values more than 200 N per briquette. The values varied mostly by ± 15 to 20% from the average value of the sample. Dutta and Chokshi[10] get the highest strength (978 N per briquette) for briquettes prepared by PVA as binder.

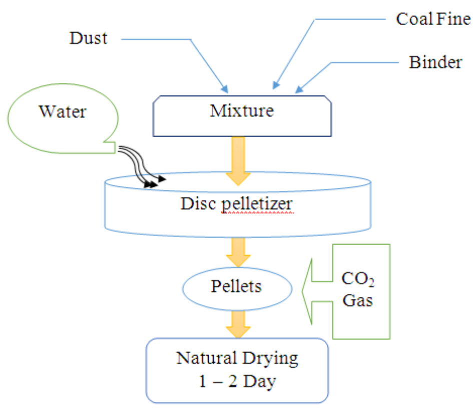
Using two binders was found very common for achieving good properties in a pellet. The proportion of each binder was taken randomly without specific criteria. The present paper attempts to highlight the use of two binders in various proportion for producing cold bonded iron oxide-coal composite pellets using Taguchi Method and MINITAB 15 software.

II. Briquetting / Pelletizing

Binder is playing a vital role for making the pellet. Binders must satisfy the following requirements[6]:

1. Mechanical properties: To protect pellets from deformation under load, resistance to disintegration/fracture by impact and compression, resistance to abrasion, compressive strength etc.
2. Chemical composition: A good binder should not increase silica and P, S , As etc into product pellets.
3. Metallurgical performance: A good binder should maintain pellet's metallurgical properties, such as high reducibility, little swelling, and little pressure drop during reduction.
4. Processing behavior: Adding, mixing, dispersion of binder, green ball preparation, pellet drying, etc., should not be complicated or essentially change conventional pellet production circuit. Good thermal stability is also a desirable property.
5. Cost factor: Price of binder should be reasonable for iron pellets production. It should be easily available in the nearby market.

Flow Sheet for pellet making



Cold bonded pelletizing technique has some specific features in contrast to the traditional pelletizing technique of iron ores as follows:

- Materials are bonding with binder at low temperature by phsico-chemical changes,
- Balling of fines are done under normal atmospheric conditions,
- Pellets are self-hardening at room temperature or at low temperature, and
- No fuels are used for hardening the pellets.

Cold bonding techniques is used for iron ore-coal composite pellet. This is a newly developed process. In conventional process, pellets are prepared using iron ore fines (may be with flux addition) and binder. Composite pellets mean pellets containing mixture of iron ore fine and carbonaceous material (i.e. coal, charcoal, or coke etc.) fines, along with suitable binder. These can be prepared only by *cold bonding techniques* i.e. bonding is done at room temperature or low temperature. The composite cold bonded pellets are used as feed material in rotary hearth furnace, where reduction takes place within 10 to 20 minutes to produce iron nuggets. The process is known as ITmk3, jointly developed by Kobe Steel Japan and Midrex Direct Reduction Corporation USA[12] . Kumar et al[13] had made briquettes at JSW Steels, Vijaynagar, India using mill scales with starch and molasses as binder. The briquettes were hardened by heating to 200^0C for 2 hrs to drive off the moisture and strengthen the briquettes.

III. Materials

- Basic oxygen furnace (BOF) dust from Jindal Steel Works(JSW), Bellary.
- Coal (From local market)
- Molasses and Starch (from Local Market

A. *Stoichiometric Calculations (at STP)*

$$Fe_2O_3 + 3C = 2Fe + 3CO$$
$$160 \quad 36 \quad 112 \quad 84$$

$\longrightarrow$ For 160 gm Fe_2O_3, C required is 36 gm

So, for 88.57gm Fe_2O_3, C required is 19.928 gm

(88.57% Fe_2O_3 content in raw material tested by XRF)

⟶ From proximate analysis of coal,
Avg. Fixed C is 62%
62 gm fixed C in 100 gm coal
So for 19.928 gm fixed C,
Coal required is **32.142** gm.

In 100gm BOF dust contains 88.57gm Fe_2O_3
So 500gm Dust contains 442.85 gm Fe_2O_3

Hence C required is 160.71gm (As per stoichiometric calculation)

B. *Taguchi Method*

The Taguchi method was developed by Genichi Taguchi, Japan. This method has been widely utilized in engineering analysis and consist of a plan of experiments with the objective of acquiring data in a controlled way, in order to obtain information about the behavior of a given process[18].The Taguchi design involves orthogonal arrays to organize the parameters affecting particular property of interest and the levels at which they varies. It allows the selection of the necessary data to determine the factors affecting product quality the most with a minimum number of experimentations. So, it saves time and resources.Tosum and Ozler[17] used the Taguchi method to investigate multiple performance characteristics and the improvement of optimal cutting parameters in hot turning operations. Srinivas and Venkatesh[18] proposed the efficient use Taguchi's parameter design to obtain optimum condition because it leads to minimum number by experimental and lower cost. Ross[19] review the optimization method of the manufacturing parameters using Taguchi method. He found that the experiment design of the orthogonal array of the Taguchi method can identify the significant foaming parameters the adjusted the process.

C. *Steps for Taguchi Method [20]*

1. Problem identification,
2. Brain-storming (identifying: factors, factor levels, possible interactions, objectives),
3. Experimental design (choosing orthogonal arrays, and designing of experiments),
4. Run of the experiments and analyze the results,
5. Confirmation (i.e. reproducibility) runs.

D. *Selection of Parameters and Levels*

It was identified by fish bone diagram, the process parameters which will influence strength and shatter index of the briquettes. Use of one organic binder is not giving good results.Combination of organic binders are used, aiming for better results. The binders along with their levels are shown in Table1.

Table 1: Selected Parameters and Their Levels

Parameters	Level-1	Level-2	Level-3
Binder-S (Starch)	2.5%	5.0%	7.5%
Binder-M (Molasses)	2.5%	5.0%	7.5%

S **Selection of Orthogonal Array**

E. *Selection of Orthogonal Array*

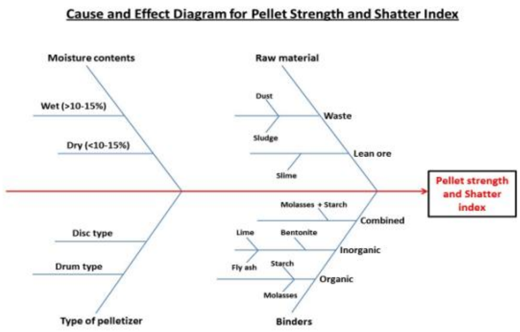


Fig. 1: Cause and Effect Diagram

After identification of the problem, factors contributing can be found out with the help of cause and effect diagram. Dhole, Naik and Prabhawalkar[21] has used the similar approach of pointing the affecting parameters out by formulating cause and effect diagram. Cause-effect diagram is generally used for the selection of affecting parameters on the property of interest. In this study two properties of interest: strength and shatter index are the importance, but eventually both properties are getting affected by the similar factors. Figure 1 shows the cause-effect diagram for the pellet strength and shatter index as properties of interest and all branches shows the factors affecting pellet strength and shatter index.

Further design matrix needs to be constructed depending upon the number of factors and levels of them. This specially designed matrix is called orthogonal array (OA). Commonly used OA includes one of the L4, L9, L12, L18, and L27 arrays. The columns in the OA indicates the factor and its corresponding levels, and each row in the OA constitutes an experimental run which is performed at the given factor combination and their current levels.

Typically either 2 or 3 levels are chosen for each factor. There are two different organic binders used and each has three different levels. So, total nine experiments can be performed including all possibilities to check the effect of different combinations on the properties of interest i.e. pellet strength and shatter index. All the experiments are performed as such they are only nine. Using standard catalogue of Taguchi orthogonal array in software Minitab 15 is used the L9 orthogonal array for the experimentations as shown in Table 2.

Table 2: L9 Orthogonal Array

Experiment Run	Starch % levels	Molasses % levels
1.	2.5	2.5
2.	2.5	5.0
3.	2.5	7.5
4.	5.0	2.5
5.	5.0	5.0
6.	5.0	7.5
7.	7.5	2.5
8.	7.5	5.0
9.	7.5	7.5

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IV. EXPERIMENTAL DETAILS

The material used for this experiment was JSW's BOF dust. Coal was mixed as per the stoichiometric calculation and the critical amount of water and binder were added. Cylindrical shaped briquettes were prepared using a die and punch assembly by giving single impact (manually) to the moist powder mixture. For selection of the proper binder, initially BOF dust coal composite briquettes were prepared with the fixed ratio of total iron and fixed carbon (i.e. $Fe_{tot}/C_{fix} = 3.19$). Large numbers of trials (i.e. briquette making) were taken for proper selection of binder. Diameter and height of the briquettes are 9.75 x 10^{-3} m and 11 to 12 x 10^{-3} m respectively.

In cold bonding process, the composite pellets were hardened due to the physico-chemical changes of the binder at slightly elevated temperature (400 to 500 K). Details can be seen in elsewhere[16].

V. RESULTS AND ANALYSIS

Orthogonal array generated using Minitab 15 software and subsequent experiments performed. The compressive strength values of composite briquettes represent the average of three measurements. Two output properties namely strength and shatter index are measured and results are presented in Table 3.

Minitab 15 statistical software is used for the analysis of the results. The graphs generated by the software includes individual and interaction plots of data means as well as individual and interaction plots of Signal to Noise ratio for strength and shatter index. The strength considered to be maximum and shatter index to be minimum.

Table 3: Experimentation Results

Experiment Run	Strength (N/briquette)	Shatter Index
1.	451.26	0.84
2.	1196.82	0.18
3.	853.47	0.4
4.	794.61	0.53
5.	1059.48	0.84
6.	784.8	0.86
7.	1010.43	0.87
8.	1167.39	0.4
9.	873.09	0.35

The individual plot for strength, makes clear that increasing starch percentage individually gives increasing trend while for molasses percentage it gives peak at 5% and then falls down. On the other hand, individual plot for shatter index shows that increasing starch percentage gives peak at 5% and then decreases, while increase in molasses percentage gives the minimum value at 5% and again elevates up.

Figure 2 shows all the nine strength readings for different combinations of the binder percentage. It indicates that the highest pellet strength is obtained with 5% molasses + 2.5% starch. Also, 5% molasses individually gives higher strengths irrespective of starch percentage. Similarly, 7.5% Starch individually gives higher strengths as well.

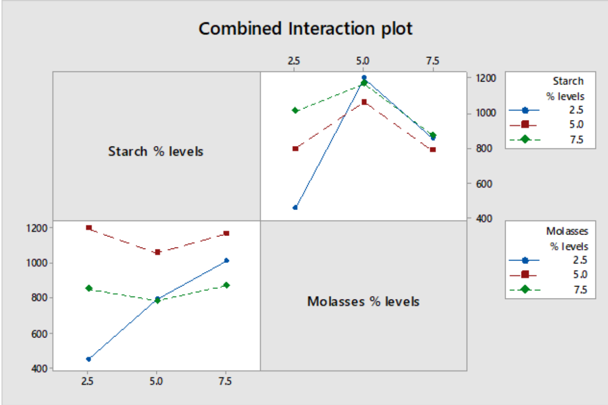

Fig. 2: Combined interaction plot for pellet strength

Figure 3 shows all the nine readings of shatter index for different combinations of the binder percentage. It indicates that the lowest Shatter index is obtained with combination of 5% molasses and 2.5% starch. Also, 5% molasses individually gives lower shatter index irrespective of starch percentage. Similarly, 2.5% starch individually gives lower shatter index as well.

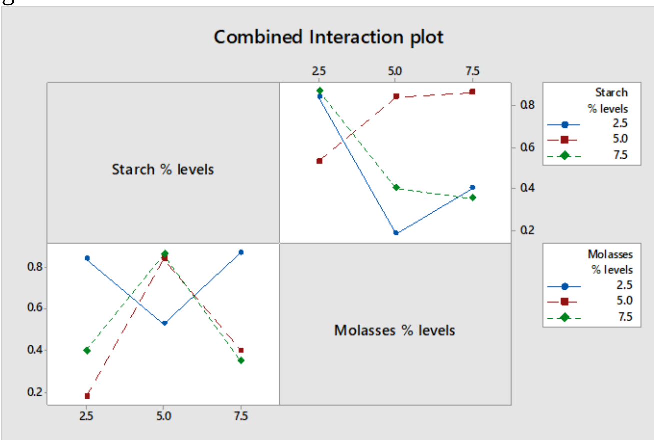

Fig. 3: Combined interaction plot for shatter index

In Taguchi's design method the design parameters (factors that can be controlled by designers) and noise factors (factors that cannot be controlled by designers, such as environmental factors) are considered influential on the properties. The Signal to Noise (S/N) ratio is used in this analysis which takes both the mean and the unaccounted variability of the experimental result into account. The S/N ratio depends on the quality characteristics of the product/process to be optimized. S/N ratio values will lead us to rank the combination of binders and finally to get the optimum one.

Equation for Signal to Noise ratio for characteristics lower is better can be given as follows:

$$SN_{LB} = -10 \log\left[\frac{1}{r}\sum_{i=1}^{r} y_i^{\,2}\right]$$

Equation for Signal to Noise ratio for characteristics higher is better can be given as follows:

$$SN_{HB} = -10 \log\left[\frac{1}{r}\sum_{i=1}^{r} \frac{1}{y_i^{\,2}}\right]$$

Considering individual plot for SN ratio of strength, it is clear that with increase in starch percentage, it shows upward trend. While increase in molasses percentage gives maximum reading at 5% and reduces there on. Also individual plot for SN ratio for shatter index, shows that with increase in starch percentage, it shows downward trend initially and then elevates, while with increase in molasses percentage, strength increses up to 5% then declines.

Figure 4 is the interaction plot of signal to noise ratio for all different combinations of binder percentages for strength. Large SN ratio shows large signals and low noise which ultimately refers to higher strength readings. Here also, same results are obtained as discussed in the interaction plot of data means for strength.

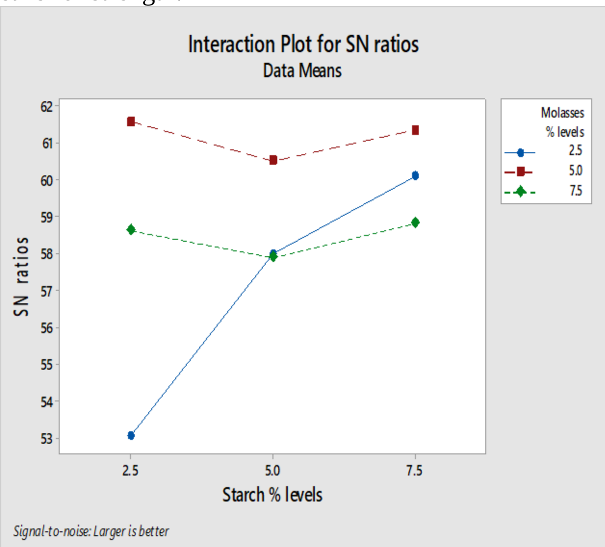

Fig. 4: Interaction plot of S/N ratio for pellet strength

Figure 5 is the interaction plot of signal to noise ratio for all different combinations of binder percentages for shatter index. Small SN ratio shows small signals and uniform noise which ultimately refers to low shatter index readings. Here also, same results are obtained as discussed in the interaction plot of data means for shatter index.

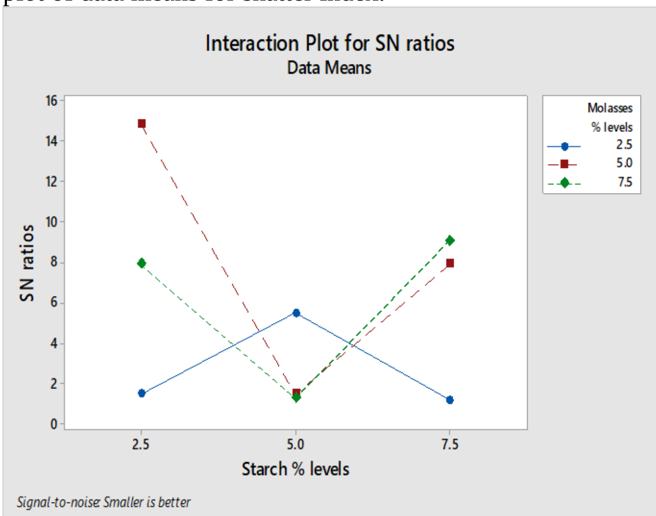

Fig. 5: Interaction plot of S/N ratio for shatter index

Table 4: Ranking order considering strength as priority

Rank	Experiment Run	Strength (N/briquette)	Shatter Index
1	2	1196.82	0.18
2	8	1167.39	0.4
3	5	1059.48	0.84
4	7	1010.43	0.87
5	9	873.09	0.35
6	3	853.47	0.4
7	4	794.61	0.53
8	6	784.8	0.86
9	1	451.26	0.84

Table 5: Ranking order considering shatter index as priority

Rank	**Experim ent Run**	**Strength (N/briquette)**	**Shatter Index**
1	2	1196.82	0.18
2	9	873.09	0.35
3	3	853.47	0.4
4	8	1167.39	0.4
5	4	794.61	0.53
6	1	451.26	0.84
7	5	1059.48	0.84
8	6	784.8	0.86
9	7	1010.43	0.87

The aim was to select optimum combination of the binder percentages for the higher strength and low shatter index. Tables 4 to 6 show the ranking order for both desired properties individually as well as considering both simultaneously.

Since both the properties are equally important, for considering combined effect of both, the sum of the ratio-1 and ratio-2 is considered and compared with each other for rankings.

$$Ratio - 1 = \frac{strength\ reading\ for\ specific\ exp.run}{maximum\ strength\ reading}\ (always\ \leq 1)$$

$$Ratio - 2 = \frac{minimum\ shatter\ index\ reading}{shatter\ index\ reading\ for\ specific\ exp.run}\ (always\ \leq 1)$$

VI. CONCLUSION

Pellets are made using fines and hence binder is very important to provide strength for easy handling. Use of two binders is a trend and the proportion of each binder for making good pellet must be used in a justified logical way. Using Taguchi method is one such way. The response parameters, strength and shatter index in briquette are measured with various binder combinations using 3x3 full factorial L9 orthogonal array. The experimental and analytical results lead to the following conclusion:

- Individually 7.5% starch and 5% molasses binder are given maximum strength while individually 2.5% starch and 5% molasses gives minimum shatter index.
- 5% molasses individually gives lower shatter index irrespective of starch percentage. Similarly, 2.5% starch individually gives lower shatter index as well. Additionally, combination of 2.5% starch and 5% molasses gives maximum strength and minimum shatter index.
- From plots of SN ratios, individually 7.5% starch and 5% molasses are giving maximum strength while individually 2.5% starch and 5% molasses gives minimum shatter index.
- From interaction plot of SN ratios, 5% molasses individually gives lower shatter index irrespective of starch percentage. Similarly, 2.5% starch individually gives lower shatter index as well. Additionally, combination of 2.5% starch and 5% molasses gives maximum strength and minimum shatter index.
- From the ranking table if only strength is priority as the response parameter, the best combination of binder is 2.5% starch and 5% molasses with 1196.82 N/briquette.
- From the ranking table if only shatter index is priority as the response parameter, the best combination of binder is 2.5% starch and 5% molasses with 0.18.
- From the final ranking table, if both the response parameters are considered equally, then also the combination of binder 2.5% starch and 5% molasses is the most optimum one.

Nomenclature

r = number of tests in a trial

y_i = i^{th} observation

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