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Utilizing Taguchi method and Regression Analysis for Optimizing Sand Mould Flowability

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Abstract

Parameters of the moulding process in foundry are usually determined by trial-and-error method, and this way contributes to time taken and adds further cost for production sand. The present work represents an attempt to optimize sand moulding parameters in terms of compactability, compaction time, and air pressure, and to study effect of these factors on the green sand flowability using L4 design of experiments. Regression model, Taguchi method, and experimental verification were used to investigate flow property of sodium bentonite-bonded BP-quartz sand for sand moulding.
Analysis of variance (ANOVA) was employed to measure significance and contributions of different moulding variables on flowability of green sand. The values obtained showed that the compaction time factor significantly affected flowability of green sand while compactability and air pressure have slight effects. The comparison results of Taguchi method, regression predictions and experiments exhibited good agreement.

Keywords: Green sand, Moulding factors, Flowability, Taguchi method, ANOVA

1. Introduction

The sand casting is a method used for producing different kinds of castings, and over 60% of all castings are obtained in the foundry industry by sand casting process. The sand used fills the model, is simply silica sand with amount of binder [1, 2]. The advantages of the sand mould in comparison to die mould are low material cost due to availability of the sand, ability of casting complex geometry of different metals, and ease of sand moulding process [3]. Sand mould properties and castings quality are usually influenced by optimization of sand moulding factors [4]. Green sand flowability represents an ability of the sand flow into around pattern during sand making process [5]. Flowability property of green sand helps for obtaining green sand mould has profile of pattern without break during separation the mould from the model [6]. Flowability of the green sand can improve the production process in foundry using Design Of Experiments DOEs, and the regression analysis [7, 8]. DOEs include full-factorial, fractional-factorial, Box-Behnken, central composite, and others [9]. Many Researchers have used DOEs, Taguchi method and the regression analysis for specifying a set of process parameters to improve quality of the green sand mould [10, 11]. DOEs were performed by Chate et al. to permit smallest number of experiments, statistical significance was conducted to manage moulding process of sand, and ANOVA method was used to statistically verify the model [12]. Experimental and analytical studies based on Taguchi method were used to investigate effect of water and bentonite content on the sand mould properties in terms of green compression strength, permeability, and mould hardness and their effect on the casting quality [13, 14]. Khare et al conducted experiments to investigate green sand factors of green strength, clay content, and casting temperature and analyzed by ANOVA method. They found the green strength of the sand mould significantly reduce casting defects [15]. Reddy et al used Taguchi method and conducted experiments to examine the factors of fineness number of grain, percentage of binder, and iron oxide. They used ANOVA and regression analysis and found that collapse with surface roughness can be obtained by managing the mentioned factors [16]. Abdulamer used factorial design of experiments reported by Taguchi method to predict effect of variation of the moulding parameters under various conditions on the sand mould properties [17]. Bhedasgaonkar et al. studied green sand factors and their effect on sand properties using Taguchi method. They found that values of moisture content, green compression strength, permeability number, and sand mould hardness number are 4.7%, 1400gm/cm^2, 140, and 85 respectively [18]. Singaram optimized content of moisture 2-4 %, compressive strength 700-1200 g/cm^2 and sand mould hardness 60-100 based on Taguchi method and artificial neural network techniques [19]. Ohdar et al used a multi-objective genetic algorithm to study effect of sand mixing time, content of moisture, clay and coal dust focusing on permeability and green compression strength [20]. Saikaew et al. used mixture experimental design, Response Surface Methodology RSM, and error propagation to determine change effect of content of bentonite and water on the sand moulding sand to reduce castings waste. They found that 93.3%, 5%, and 1.7% of recycled sand, bentonite, and water respectively gave 53,090 N/m^2 of compression strength and 30 AFS of permeability [3]. The present work used regression model, Taguchi method, and experimental verification to optimize flowability of green sand based on determining the optimal levels of sand moulding factors.

2. Experimental Design

The moulding materials used in the current investigation are BP- Quartz sand, and 8% of Sodium Bentonite. The sand used is mixed with bentonite and 1.5% of water by a mixing machine for preparing the sand mixture required to test flowability of green sand. Orlov flowability test was used, during which a 50mm diameter tube test is filled with prepared sand mixture through sieve, and funnel. The tube test is equipped with graded pattern, and the difference between surfaces of pattern is 25mm. The mixture of green sand is then subjected to pressure by pressing machine. The obtained sand sample has two distinct surfaces, Orlov flowability test depends on the ratio of hardness measurement between bottom to upper surfaces of the green sand sample. The target of using regression analysis and Taguchi method is enhancing the sand flowability for uniformly fill the mould cavities to reduce defects instead of scrap in the final castings. Design of experiments reduces the need for a trial-and-error approach, and helps identify ideal parameters that influence the sand mould flowability. This involves determining the optimum levels of factors of compactability, compaction time and air pressure listed in table 1. Design of experiments was used to prepare four series of green sand samples, and each series was subjected to the Orlove flowability test as mentioned in table 2.

Table 1.
Factors and their levels

		Factors		
		Compactability %	**Compaction time (*s*)**	**Air Pressure (*bar*)**
Levels	-1	33	7	3.5
	+1	43	9	5.5
Intervals		10	2	2

The L4 design matrix listed in table 2 is a structured approach of design of experiments used to create relationships between variables and response. As is described in figure 1, the characters x_c, x_t, and x_a stand for the independent parameters of compactability, compaction time and air pressure respectively, while the response y_f presents the flowability outcome.

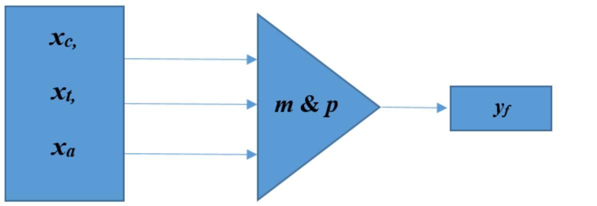

Fig. 1. Input-output model for sand mould process

Table 2.
L4 Design matrix of experiments and response outcome

No.	**Variables**			**Response**
	x_c %	x_t (s)	x_a (*bar*)	y_f %
1	-1	-1	-1	60.92095
2	-1	+1	+1	80.59039
3	+1	-1	+1	69.31069
4	+1	+1	-1	80.73411

The equations (1-4) are used for estimation of parameters coefficients of p_0, p_c, p_t, and p_a. where p_c, p_t, and p_a are representing coefficients of parameters of compactability, compaction time and air pressure respectively, while p_0 is constant value.

$$y_{f1} = p_0 - p_c - p_t - p_a = 0.60921 \quad (1)$$

$$y_{f2} = p_0 - p_c + p_t + p_a = 0.80590 \quad (2)$$

$$y_{f3} = p_0 + p_c - p_t + p_a = 0.69311 \quad (3)$$

$$y_{f4} = p_0 + p_c + p_t - p_a = 0.80734 \quad (4)$$

The parameters coefficients p_0, p_c, p_t, and p_a are determined by using the matrix outcome by the simultaneous solution of equations 1+2+3+4, 1+2-3-4, 1-2+3-4, and 1-2-3+4 respectively.

$$p_0 = \frac{0.60921 + 0.80590 + 0.69311 + 0.80734}{4} = 0.72889$$

$$p_c = \frac{0.60921 + 0.80590 - 0.69311 - 0.80734}{-4} = 0.021335$$

$$p_t = \frac{0.60921 - 0.80590 + 0.69311 - 0.80734}{-4} = 0.07773$$

$$p_a = \frac{0.60921 - 0.80590 - 0.69311 + 0.80734}{-4} = 0.020615$$

3. Regression Analysis

Equation 5 describes the full factorial design and its significance, that have 8 regression coefficient and corresponds to 8 experiments

$$y_f = p_0 + p_c x_c + p_t x_t + p_a x_a + p_{ct} x_c x_t + p_{ca} x_c x_a + p_{ta} x_t x_a + p_{cta} x_c x_t x_a \quad (5)$$

Equation 6 represents the fractional factorial design and its simplification, which represents general function used to express the effect of factors and their levels on the outcome.

$$y_f = p_0 + p_c x_c + p_t x_t + p_a x_a \quad (6)$$

Equation 7 display how regression models are used to express the effect of factors on the outcome, the equation can have up to four parameters by substitution of parameters coefficients of p_0, *pc,* p_t and p_a so equation 6 becomes

$$y_f = 0.72889 + 0.021335\, x_c + 0.07773\, x_t + 0.020615\, x_a \quad (7)$$

Variance of the data collected S^2_{yf} from the experiments is the mean of the square of deviations to the degree of freedom *DOF*.

$$S^2_{yf} = \frac{\text{mean of square of deviations}}{DOF} \quad (8)$$

where: *DOF*= *n-1*, and *n* is the number of experiments, the contributions to the variance of data experiments are given by equation 9.

$$SST = SSc + SSt + SSa \quad (9)$$

$$SSc = 4 \times (p_c^2) \quad (10)$$

$$SSt = 4 \times (p_t^2) \quad (11)$$

$$SSa = 4 \times (p_a^2) \quad (12)$$

where *SST* is total sum of squares of deviations, *SSc, SSt*, and *SSa* are mean of squares due to variation in factors levels x_c, x_t and respectively.

4. Analysis of Variance (ANOVA)

Effect of various moulding factors on green sand flowability has been investigated. Table 3 presents ANOVA that carried out to analyse the data collected from the experiments. It explains the contributions and highlights the significance of different factors to the variance in flowability data. ANOVA is statistical analysis method usually used to compare means to examine the effect of two, or more factors on a response and to identify whether there are significant differences. The influence of these factors can be gauged by the contribution of each term to the variance. In the current study, the results of ANOVA of the various sand moulding parameters, namely: compactability, compaction time and air pressure indicate to a statistically significant variance of flowability for compaction time parameter. It is found that the compaction time has the largest effect while air pressure and compactability have the smallest effect on the flowability of sand mould.

Table 3.
ANOVA Table

Mean of squares of deviations	Contribution *Adj SS*	The relative contributions *P %*	*DOF*	Variance S^2_y
SST	*0.027688*	*100*	*3*	*0.009229*
SSc	*0.001821*	*6.575769595*	*3*	*0.000607*
SSt	*0.024168*	*87.28480154*	*3*	*0.008056*
SSa	*0.0017*	*6.139428864*	*3*	*0.000567*

Equation 13 presents regression model that developed by Taguchi method to find relationship between dependent variable of flowability of green sand, and one, or more independent moulding parameters of compactability, compaction time, and air pressure.

$$y_f = -0.1479 + 0.4267\, x_c + 0.07773\, x_t + 0.02062\, x_a \quad (13)$$

The results listed in table 4 show comparison between data achieved from experimental, regression equation 7, and Taguchi prediction method equation 13. Figure 2 graphically presented data of table4, it is found a good match between experimental results, regression model, and Taguchi method.

Table 4.
Comparison between practical, regression model & Taguchi predication

No.	Variables		Practical		Regression *Eq. 7*	Predication *Eq. 13*
	x_c %	x_t (s)	x_a bar	y_f (%)	y_f (%)	y_f (%)
1	*-1*	*-1*	*-1*	*60.92095*	*63.0592*	*60.9191*
2	*-1*	*+1*	*+1*	*80.59039*	*82.7282*	*80.5891*
3	*+1*	*-1*	*+1*	*69.31069*	*67.39555*	*69.3101*
4	*+1*	*+1*	*-1*	*80.73411*	*78.81855*	*80.7321*

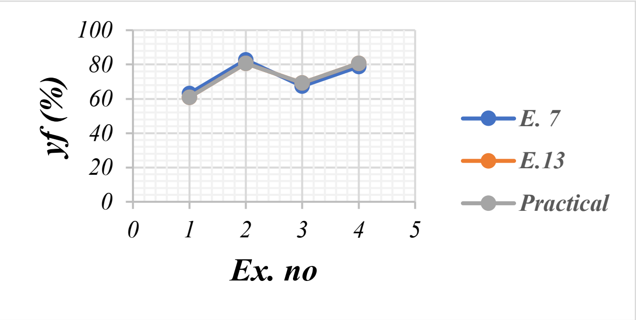

Fig. 2. Flowability Vs Ex. no.

The results for plot of main effects and surface plot are shown in figures 3 and 4 respectively. Figure 3 indicates that the main effects occur with change in levels of compactability, compaction time, and air pressure. The maximum flowability of 80.73% was obtained from experiment no. 4, and its levels are +1, +1, and -1 for compactability, compaction time, and air pressure, respectively. On the other hand, experiment no. 1, and its levels -1, -1, and -1 of sand moulding factors give 60.92% minimum value of flowability property of green sand. Figure 4 shows the surface plot, it is found that the flowability percentage increased when control both factors of compactability at level 1 or level 2 and air pressure at level 2 or level 1 respectively.

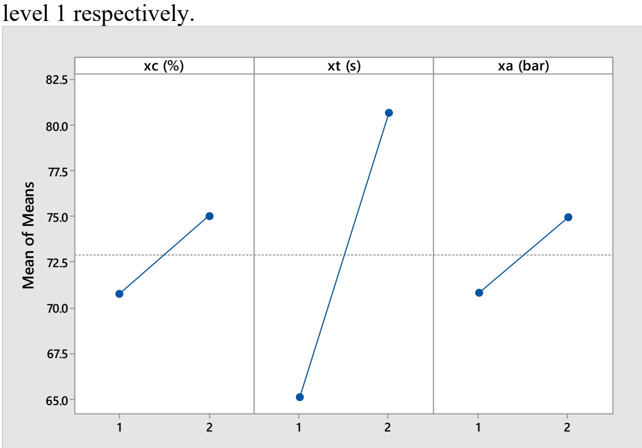

Fig. 3. Plot of main effects

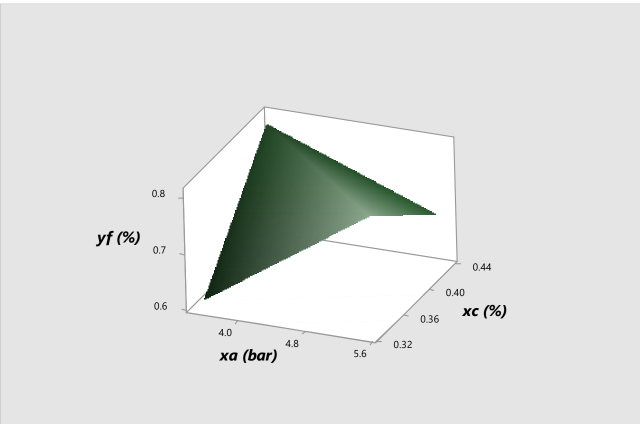

Fig. 4. Surface plot

5. Conclusions

The combination of Taguchi method and regression analysis provides regular scope to enhance flowability of green sand. Design of experiments facilitated the examination of relationships between sand moulding factors, and their impact on the dependent variable of flowability.

The results obtained by predictions, Taguchi method, and experiments confirmed the presence of a significant effect of compaction time, while referring a relatively small impact of compactability, and air pressure on sand flowability. Controlling air pressure and compactability levels can influence flowability percentages, indicating that the specific interaction of these independent variables results in remarkable increases in flowability. This extensive analysis offers important impressions for optimizing moulding factors to improve sand flowability.

A comparison between regression model predictions, Taguchi method, and experimental values shows a strong match among these various methods.

6. Conflict of interest

The authors declare that they have no conflict of interest.

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