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Optimizing Sand Moulding Process through Regression Models and Destructive Testing

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Abstract

The main objective of the present study is enhanced of the sand moulding process through addressing the sand mould defects and failures, ultimately lead to improve production of the sand castings with well-defined of pattern profiles. The research aimed to reduce the cost and energy expenditure associated with the compaction time of the sand moulding process. Practical destructive tests were conducted to assess properties of the green sand moulds. Linear regression and multi-regression methods were employed to identify the key factors influencing the sand moulding process. The proposed experimental destructive tests and predicted regression methods facilitated measurement of the green sand properties and enabled evaluation of the effective moulding parameters, thereby enhancing the sand moulding process. Factorial design of experiments approach was employed to evaluate effect of parameters of water content and mixing time of the green sand compaction process on the mechanical properties of green sand mould namely the tensile strength, and compressive strength.

Keywords: Green sand mould, Moulding parameters, Design of experiments, Destructive tests, Regression methods

1. Introduction

Sand moulding is most employed metal casting process in manufacturing and constituting over 70% of all castings. The main advantages of sand moulding process are cost-effectiveness as sand is cheap material, due to availability of the sand on the earth crust. The sand moulding process is a versatile method suitable for mass production and allows for a wide range of components size from very small to the large, shaped castings with intricate design, and unique properties that not attainable through other methods. The sand used for moulding process is combined with a typical mixture of clay and water [1- 3]. Silica sand cannot be used alone and must be mixed with bentonite to enhance the binding properties of sand used in the moulding process. The incorporation of various types of bentonite binder material to the mixture of green sand for providing favourable cohesion, bonding strength and ensure compatibility to maintain the mould cavity's shape after removal the pattern [4, 5]. Composition of the green sand and optimization of the sand moulding process factors directly influence sand mould properties and ultimately quality of the final castings [6]. Several studies have been conducted in the last years to find the optimum variables of sand moulding process and improve the sand casting quality by using different methods [7]. Taguchi method is involving signal to noise ratio S/N ratio, and the orthogonal array design, the method is limited to single objective function maximization within experimental settings [8]. Abdulamer used Taguchi method to obtain an effective, and appropriate factors of sand moulding to improve properties of the green sand mould such tensile strength, compressive strength, and permeability [9]. Kumar et al. have utilized Taguchi method to optimize properties of green sand casting process in foundries involving green mould hardness, strength, and permeability [10]. Other techniques such as RSM Response Surface Methodology can be employed to determine optimum process factors like bentonite and water content for optimize production of specific castings like the grey cast pump impellers [11]. Central composite design of experimental method has been also employed to study effect of predominant parameters like mixing time, water, and bentonite content on properties of sand mould [12]. Abdulamer used design of experiments to examine effect of different moulding parameters on green sand flowability by using non-destructive tests [13]. Sand moulding parameters have a direct effect during moulding process of the green sand. Bast et al. employed sand detection compaction sensor to examine various green sand moulding variables during moulding process for obtaining castings to prevent defects and failure [14]. The current research focused on studying impact of various moulding factors of mixing time, and water percentage on the mechanical properties of the sand mould by factorial experiments design method. Destructive experimental tests, linear and multi-regression methods have been adopted to predict effective sand moulding factors.

2. Methodology

The target of the experiments was to investigate impact of water content and mixing time on tensile, and compressive strength of the sand mould. Table 1 shows the factors of water content, mixing time and their levels.

Table 1.
Factors and their levels of the sand moulding

Levels	Factors: Water content % x_1	Factors: Mixing Time (min) x_2
1	1	1
2	1.5	3
3	2	5
4	2.5	7

The green sand mixture was involved of BP Quartz sand, Active Clay Content (ACC) Bentonite binder and water. The BP sand used in the experiments had 24mm an average grain size and ACC bentonite binder contained 81% Montmorillonite. The mixing process of BP sand, ACC bentonite and water was carried out using a mixer machine. In each experiment a predetermined amount of BP sand, 7% ACC bentonite and an appropriate quantity water were charged into the mixer machine. The constituents were mixed for a specific time based on experiments design listed in table 2. Mass of the green sand mixture for each experiment listed in table 2 was measured and placed in a 50mm diameter tube test to obtain standard cylindrical sand specimens with height, and diameter of 50mm. Mixture of the green sand was filled into the tube test, then the mixture compacted by using a sand rammer machine. The compaction process ensured that the green sand achieved compaction level and a consistent density. Once the mixture compacted, the green sand sample was carefully removed from the tube test to measure mechanical properties, including tensile strength (y_{Ts}) and compressive strength (y_{cs}) of green sand mould. The obtained standard sand sample was placed in a universal strength machine to evaluate the mechanical properties of the green sand. Compressive and tensile strength tests were conducted three times on the obtained cylindrical green sand samples, and the dispersion properties were found to be less than 5%, the average results were recorded and presented in table 2.

Table 2.
Experiment's plan and measured properties of the green sand

S/No	Factors: x_1	Factors: x_2	Sand properties: y_{cs} (Mpa)	Sand properties: y_{Ts} (Mpa)
1	1	1	0.0932	0.0014
2	1	3	0.1030	0.0017
3	1	5	0.1373	0.0019
4	1	7	0.1618	0.0023
5	1.5	1	0.1128	0.0020
6	1.5	3	0.1079	0.0016
7	1.5	5	0.1765	0.0023
8	1.5	7	0.1667	0.0024
9	2	1	0.1275	0.0022
10	2	3	0.1226	0.0023
11	2	5	0.1177	0.0019
12	2	7	0.1373	0.0021
13	2.5	1	0.1275	0.0023
14	2.5	3	0.1373	0.0022
15	2.5	5	0.1618	0.0029
16	2.5	7	0.1767	0.0033
Sum	28	64	2.1676	0.0348

3. Linear and Multi-Regression Analysis

The linear regression of least square method is used for fitting straight line to set of points (x_i, y_i). The mathematical regression of straight line is:

$$y = a_0 + a_1 x \quad (1)$$

where ($a_0 + a_1 x$) is approximate value, a_0 is constant value denote into intersection with (y) actual value and a_1 is slope of straight line. a_1 and a_0 are parameters control position of straight line in x-y plane, and these regression parameters can be calculated by equation 2 and 3 respectively.

$$a_1 = \frac{n \sum_i^n x_i\, y_i - \sum_i^n x_i \cdot \sum_i^n y_i}{n \sum_i^n x_i^2 - \left(\sum_i^n x_i\right)^2} \quad (2)$$

where n is the number of data points

$$a_0 = \bar{y} - a_1 \bar{x} \quad (3)$$

and,

$$\bar{y} = \frac{\sum_i^n y_i}{n} \quad (4)$$

and

$$\bar{x} = \frac{\sum_i^n x_i}{n} \quad (5)$$

Table 3 is used to calculate regression coefficient of a_1 and a_0 through solution of equations 2-5 respectively.

Table 3.
Values of the moulding parameters and compressive strength

S/No	$x_1 x_2$	$(x_1)^2$	$(x_2)^2$	$x_1 y_{cs}$	$x_2 y_{cs}$	$(y_{cs})^2$
1	1	1	1	0.0932	0.0932	0.0087
2	3	1	9	0.1030	0.3090	0.0106
3	5	1	25	0.1373	0.6865	0.0188
4	7	1	49	0.1618	1.1326	0.0262
5	1.5	2.25	1	0.1692	0.1128	0.0127
6	4.5	2.25	9	0.16185	0.3237	0.0116
7	7.5	2.25	25	0.26475	0.8825	0.0311
8	10.5	2.25	49	0.25005	1.1669	0.0278
9	2	4	1	0.2550	0.1275	0.0162
10	6	4	9	0.2452	0.3678	0.0150
11	10	4	25	0.2354	0.5885	0.0138
12	14	4	49	0.2746	0.9611	0.0188
13	2.5	6.25	1	0.3187	0.1275	0.0162
14	7.5	6.25	9	0.3432	0.4119	0.0188
15	12.5	6.25	25	0.4045	0.809	0.0262
16	17.5	6.25	49	0.4417	1.2369	0.0312
sum	112	54	336	3.8596	9.3374	0.3041

The linear regression equation of the compressive strength y_{cs} based on the sand moulding parameters x_1 and x_2 have been determined through inserting of the measured regression coefficients a_1 and a_0 in equation 1. The relationships between compressive strength of green sand mould, and factors of water content and mixing time were described in equations 6, and 7 respectively.

$$y_{cs1} = 0.1123 + 0.0133\, x_1 \quad (6)$$

$$y_{cs2} = 0.1021 + 0.0083\, x_2 \quad (7)$$

The least square procedure of linear regression equation can be extended into multiple linear regression equation when (y) is function of two or more variables as described in equation 8.

$$y = \alpha_0 + \alpha_1 x + \alpha_2 x_2 + \cdots + \alpha_n \alpha x_n \quad (8)$$

The regression coefficients α_2, α_1, and α_0 are calculated by solving equations 9, 10, and 11 simultaneously.

$$\sum_i^n y_i = \alpha_0\, n + \sum_i^n \alpha_1\, x_{1,i} + \sum_i^n \alpha_2\, x_{2,i} \quad (9)$$

$$\sum_i^n y_i\, x_{1,i} = \sum_i^n \alpha_0\, x_{1,i} + \sum_i^n \alpha_1\, x_{1,i}^2 + \sum_i^n \alpha_2\, x_{1,i}\, x_{2,i} \quad (10)$$

$$\sum_i^n y_i\, x_{2,i} = \sum_i^n \alpha_0\, x_{2,i} + \sum_i^n \alpha_1\, x_{1,i}\, x_{2,i} + \sum_i^n \alpha_2\, x_{2,i}^2 \quad (11)$$

The multi linear regression equations 12, 13 and 14 were obtained by substitution of the required data from table 3 in equations 9-11 respectively.

$$2.1676 = 16\, \alpha_0 + 28\, \alpha_1 + 64\, \alpha_2 \quad (12)$$

$$3.8596 = 28\, \alpha_0 + 54\, \alpha_1 + 112\, \alpha_2 \quad (13)$$

$$9.3374 = 64\, \alpha_0 + 112\, \alpha_1 + 336\, \alpha_2 \quad (14)$$

The coefficients α_0, α_1 and α_2 of the multi-linear regression equation were then determined by simultaneously solving equations 12, 13, and 14. The obtained regression coefficients were inserted into equation 8, resulting in a multi-regression equation 15 which represents the relationship between compressive strength, water content and mixing time.

$$y_{cs3} = 0.079 + 0.0133\, x_1 + 0.0083\, x_2 \quad (15)$$

where α_0= 0.079, α_1= 0.0133, and α_2= 0.0083

Equation 15 can be utilized to predict compressive strength of green sand mould based on variation of these two moulding parameters. Table 4 provides comparison between compressive strength values of sand mould that were experimentally measured and those predicted by the linear and multi regression equations (y_{cs1}, y_{cs2}, and y_{cs3}).

Table 4.
Comparison of experimental & predicted compressive strength values

	Practical	Predicted		
S/No	y_{cs} (MPa)	y_{cs1} (MPa)	y_{cs2} (MPa)	y_{cs3} (MPa)
1	0.0932	0.1256	0.1104	0.1010
2	0.1030	0.1256	0.1270	0.1170
3	0.1373	0.1256	0.1436	0.1340
4	0.1618	0.1256	0.1602	0.1500
5	0.1128	0.1322	0.1104	0.1070
6	0.1079	0.1322	0.1270	0.1240
7	0.1765	0.1322	0.1436	0.1400
8	0.1667	0.1322	0.1602	0.1570
9	0.1275	0.1389	0.1104	0.1140
10	0.1226	0.1389	0.1270	0.1300
11	0.1177	0.1389	0.1436	0.1470
12	0.1373	0.1389	0.1602	0.1640
13	0.1275	0.1455	0.1104	0.1200
14	0.1373	0.1455	0.1270	0.1370
15	0.1618	0.1455	0.1436	0.1540
16	0.1767	0.1455	0.1602	0.1700

4. Tensile Strength

Same procedure used for determining linear and multi regression equations of compressive strength have been also employed to determine linear and multi regression equations of tensile strength of the green sand. Data listed in table 5 have been inserted in equations 2 - 5 to determine linear regression equations of the tensile strength. The relationship between property of tensile strength y_{Ts} of green sand, and factors of water content and mixing time are described in equations 16, and 17 respectively.

Table 5.
Values of the moulding parameters and tensile strength

S/No	x_1x_2	$(x_1)^2$	$(x_2)^2$	x_1y_{Ts}	x_2y_{Ts}	$(y_{Ts})^2$*E-6
1	1	1	1	0.0014	0.0014	1.96
2	3	1	9	0.0017	0.0051	2.89
3	5	1	25	0.0019	0.0095	3.61
4	7	1	49	0.0023	0.0161	5.29
5	1.5	2.25	1	0.0030	0.0020	4
6	4.5	2.25	9	0.0024	0.0048	2.56
7	7.5	2.25	25	0.0034	0.0115	5.29
8	10.5	2.25	49	0.0036	0.0168	5.76
9	2	4	1	0.0044	0.0022	4.84
10	6	4	9	0.0046	0.0069	5.29
11	10	4	25	0.0038	0.0095	3.61
12	14	4	49	0.0042	0.0147	4.41
13	2.5	6.25	1	0.0057	0.0023	5.29
14	7.5	6.25	9	0.0055	0.0066	4.84
15	12.5	6.25	25	0.0072	0.0145	8.41
16	17.5	6.25	49	0.0082	0.0231	1.09
sum	112	54	336	0.0635	0.1470	7.89

$$y_{Ts1} = 0.001265 + 0.00052\, x_1 \quad (16)$$

$$y_{Ts2} = 0.001785 + 0.0000975\, x_2 \quad (17)$$

Data listed in table 5 have been inserted in equations 9-11 to determine multi-regression equation of tensile strength. The resultant multi-regression equation 18 show relationship between tensile strength, water content and mixing time.

$$y_{Ts3} = 0.000876 + 0.00052\, x_1 + 0.0000975\, x_2 \quad (18)$$

where α_0= 0.000876, α_1= 0.00052, and α_2= 0.0000975

This equation can be used for evaluation of the tensile strength of green sand depending on the variation of these two moulding parameters. Table 6 listed comparison between tensile strength values of the green sand mould that were experimentally measured and predicted by linear and multi regression equations y_{Ts1}, y_{Ts2}, and y_{Ts3}.

Table 6.
Comparison of experimental & predicted values of the tensile strength

	Practical	**Predicted**		
S/No	y_{Ts} **(MPa)**	y_{Ts1} **(MPa)**	y_{Ts2} **(MPa)**	y_{Ts3} **(MPa)**
1	0.0014	0.0018	0.0019	0.0015
2	0.0017	0.0018	0.0021	0.0017
3	0.0019	0.0018	0.0023	0.0019
4	0.0023	0.0018	0.0025	0.0021
5	0.0020	0.0020	0.0019	0.0017
6	0.0016	0.0020	0.0021	0.0019
7	0.0023	0.0020	0.0023	0.0021
8	0.0024	0.0020	0.0025	0.0023
9	0.0022	0.0023	0.0019	0.0020
10	0.0023	0.0023	0.0021	0.0022
11	0.0019	0.0023	0.0019	0.0024
12	0.0021	0.0023	0.0025	0.0026
13	0.0023	0.0026	0.0019	0.0023
14	0.0022	0.0026	0.0025	0.0025
15	0.0029	0.0026	0.0019	0.0027
16	0.0033	0.0026	0.0025	0.0028

5. Discussion of Results

Statistical design of experiments is an effective tool used to control the behavior of sand by making the relationships between sand moulding factors and dependent properties [15, 16]. The statistical method enables exploration of multiple sand moulding parameters and their interactions. Using the statistical method saves time to predict the independent factors. It is possible to obtain green sand with desirable properties for specific applications by controlling variables [17]. The full factorial design of experiment was used for the linear regression equations [18] to analyze the impact of different factors. In this context, Dietert [19] and Parappagoudar et al [20] have introduced linear relationships to describe the value of parameter needed to conduct the experiments of sand properties. The linear regression equations are valuable statistical methods used to establish relationships between variables. The least square method has been employed to measure regression coefficients which give relationship between the dependent variable (y) and independent variables (x).
Tables 4 and 6 provide comparison between practically calculated values of compressive and tensile strength of the green sand, and the predicted values which obtained from linear and multi linear regression methods. These tables demonstrate effectiveness of regression equations for predicating properties of compressive, and tensile strength based on parameters variation of the green sand moulding. The regression methods offer advantage for calculating ideal sand moulding factors which effect the green sand properties. Regression equations can predict properties of green sand based on variation of parameters of water content and mixing time. Foundry men were able to assess strength properties and can identify the optimal conditions for obtaining desired properties of the green sand by analyzing sand moulding

parameters. The results shown in tables 4 and 6 are graphically presented in figures 1 and 2 respectively. The figures indicate that there is no big divergence between the predicted and experimental values of compressive and tensile strength of green sand. The compressive and tensile strength values predicted by regression equations showed a slight difference from the actual experimental values. The finding suggests that the regression equations employed to measure the compressive and tensile strength of green sand are effective and reliable. Experiments 7, 8, 15 and 16 yielded the highest values for compressive strength, and experiment number 1 resulted in the lowest value for compressive strength of the green sand. In this context, experiment number 15 exhibited the highest tensile strength, while experiment number 1 showed the lowest tensile strength among the experiments conducted. These findings provide valuable insights into performance of the green sand under various practical conditions and highlight range of green strength values that can be expected.

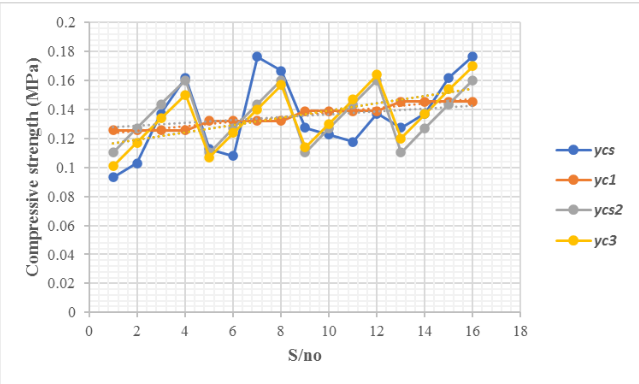

Fig. 1. Compressive strength vs experiment number

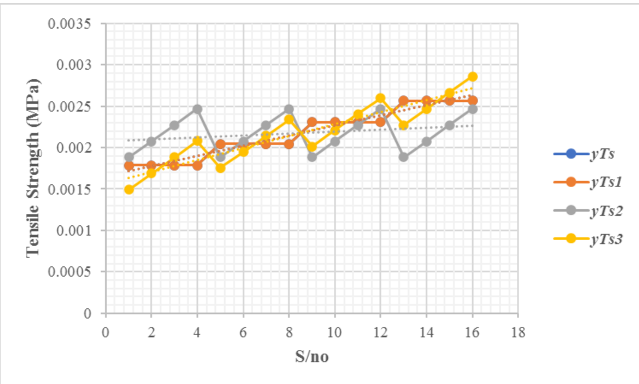

Fig. 2. Tensile strength vs experiment number

6. Conclusions

The successful implementation of regression models has proven to be a valuable statistical method for establishing relationships between variables of the green sand moulding. The foundry technician can accurately evaluate the sand moulding factors of water content and mixing time that directly impact the properties of green sand, and this has been demonstrated by using regression methods in comparison with practically calculated values of compressive and tensile strength of green sand. It was found that the interaction of first levels of water content and mixing time gave 0.0932Mpa, 0.0014Mpa the lowest values for the compressive and tensile strength of green sand, respectively.
The good alignment between experimental and predicted values for both compressive and tensile strength confirms the effectiveness of the regression models employed to measure the green sand properties.

Conflict of interest

The author declares that he has no conflict of interest.

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