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Modeling and Optimization of Phenol Formaldehyde Resin Sand Mould System

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Abstract

Chemical bonded resin sand mould system has high dimensional accuracy, surface finish and sand mould properties compared to green sand mould system. The mould cavity prepared under chemical bonded sand mould system must produce sufficient permeability and hardness to withstand sand drop while pouring molten metal through ladle. The demand for improved values of permeability and mould hardness depends on systematic study and analysis of influencing variables namely grain fineness number, setting time, percent of resin and hardener. Try-error experiment methods and analysis were considered impractical in actual foundry practice due to the associated cost. Experimental matrices of central composite design allow conducting minimum experiments that provide complete insight of the process. Statistical significance of influencing variables and their interaction were determined to control the process. Analysis of variance (ANOVA) test was conducted to validate the model statistically. Mathematical equation was derived separately for mould hardness and permeability, which are expressed as a non-linear function of input variables based on the collected experimental input-output data. The developed model prediction accuracy for practical usefulness was tested with 10 random experimental conditions. The decision variables for higher mould hardness and permeability were determined using desirability function approach. The prediction results were found to be consistent with experimental values.

Keywords: Design of experiments, Phenol formaldehyde resin, Permeability, Mould hardness, Desirability function approach

1. Introduction

Modern foundry uses chemical bonded no bake sand mould system as it has enhanced shelf life, strength, dimension accuracy and surface finish [1]. Sand moulds were preferred to permanent mould due to several technical advantages, namely, low process cost, ease of mould making, minimized constraints on part geometry and castability of different metals [2]. Sand drop defects in casting are always the result of mould hardness, which in turn is influenced by grain fineness, quantity of binder (resin and hardener), curing time, degree of ramming and so on. Parappagoudar et al. showed analyzing the influencing green sand variables, helped to control the mould hardness and permeability [3]. Barlow et al. [4] emphasized the influence of hardness to prevent the mould wall movement. Frost et al. [5] analyzed pressure and hardness distributions in sand moulds using theoretical and experimental methods. The authors observed that frictional interface between moulding sand and pattern to be the governing factors that significantly affect mould hardness. However, developed analytical method is not globally acceptable as it is limited to particular sand mould composition. Brigg et al. [6] discussed the effects of grain size and relative distribution, degree of ramming and binder content on sand mould properties.

Accurate control of moulding variables offer better sand mould properties. Dietert et al. [7] showed that density increases with mould hardness as a result of wide range of grain size than narrow range. The sand grain size and shape was found to affect mould permeability and casting surface finish [8-9]. Casting porosity was reported to increase with the increase in mould pressure, and the compacted mould does not allow the generated gasses to escape out [10]. Kandelwal and Ravi [11] found that core shrinkage and hardness are significantly influenced by the amount of binder content, than hardener. Lowe and Showman [12] showed that fine sand grain size always results in more shrinkage and less hardness for the fixed percent of binder. However, long setting time required for polymerization reactions to provide better sand mould properties is the major drawback that restricts resin bonded sand moulding, but offers dimensional stability, strength and hardness to the mould. Based on the outcome of the literature survey, it was decided to study input parameter varying simultaneously to know the complete insight of detailed process information of interaction factor effects.

Earlier studies reveal that the interaction factor effects can be determined by studying input parameters that is varied simultaneously under experimentation. Statistical design of experiments (DOE) is an effective tool to conduct minimum experiments by varying input factors between their respective levels, analyze the factor significance quantitatively, derive a mathematical expression, and validate model adequacy based on the collected input-output data. Rose and Vingas [13] applied DOE to study and analyze the binder content, geological sand origin, degree of ramming, and water content on sand mould properties. Nevertheless, mould hardness an important property has been neglected fully, and no predictive input-output expressions have been derived. Surekha et al. [14] although analyzed DOE and response surface methodology (RSM) based modeling for the phenol formaldehyde resin bonded system on different sand mould properties, neglected the grain fineness number (GFN) influence on mould hardness completely during their research work. Dabade and Bhedasgaonkar [15] employed Taguchi method to minimize the redundant simulation based computer aided tool to model and analyze the cast defects relationship with green sand mould parameters. Multiple linear and non-linear regression models were developed to study and analyze the effects of green sand [16] and cement bonded sand [17] moulding system using DOE and RSM. The results showed green compression strength to have a third order non-linear relationship with mould hardness having a good correlation coefficient. The binder and hardener reactions in sand moulds influenced majorly on casting defects, namely, blow holes, sand drop, etc. [18]. Higher mould hardness is desired to complete subsequent operations in actual foundry practice that moulds are moved from moulding to pouring section to withstand molten metal from ladle to pouring basin. Mould hardness and permeability, which are influenced by a grain fineness number, curing time, percent of resin and hardener, has not been modeled and analyzed yet in the literature. Further, predictive equations are not established for this process and accuracy has not been confirmed using practical experiments.

The appropriate set of moulding variables always results in better mould hardness, which in turn reduce the casting defects like blow holes, sand drop etc. Taguchi method optimizes the moulding sand variables to locate the highest possible tensile strength [19] and minimizes casting defects [15]. The green sand mould process variables are optimized for compression strength, permeability and mould hardness using the desirability function approach (DFA) and RSM [20]. Statistical (DOE, RSM, DFA, and Taguchi method) optimization tools follow deterministic search method with particular rules to locate the optimal solution for different manufacturing processes [15, 18-19]. The success of the DFA in the recent literature [20-21] has motivated us to locate an optimal solution for extreme values of mould hardness and permeability.

2. Experimental procedure, data collection, modeling and optimization

The present-day foundry requirements in modeling and optimization of phenol formaldehyde resin based sand mould decision variables for mould hardness and permeability were solved using the following steps:

1. The decision variables that affect the mould hardness and permeability were selected.
2. Significance test was used to statistically analyze the importance of sand mould variables.
3. ANOVA test was conducted to validate the statistical adequacy of the developed model.
4. Surface plots were drawn to study the moulding sand variables on permeability and mould hardness.
5. Mathematical equations were derived for both permeability and mould hardness, which were expressed as a non-linear function of the decision variables.
6. The derived mould hardness and permeability type predictive equations were tested with ten random experiments.
7. The optimization task for both permeability and mould hardness with regard to decision variables was determined using DFA.
8. Confirmatory experiments were conducted to measure deviation for practical utility in industries.

The systematic approach was employed after conducting pilot experiments in metal casting industries, consulting with experts from foundry personnel, and analyzing the literature. Four control variables, namely, GFN, setting time, percent of resin and resin-to-hardener ratio, affect the mould hardness and permeability critically (refer Fig. 1). The input variables and operating levels are defined and presented in Table 1

Table 1.
Input variables and corresponding levels

Sl. No	Parameters: Source	Notation	Level: Low	Middle	High
1	Grain fineness number	A	50	70	90
2	Percent of resin	B	1.8	2.0	2.2
3	Percent of hardener	C	0.8	1.0	1.2
4	Settling time	D	60	90	120

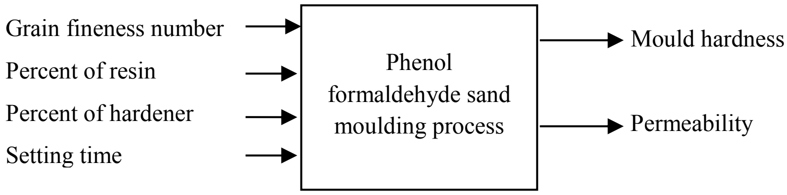
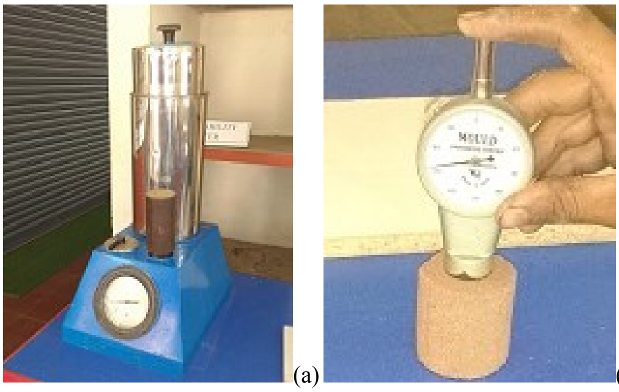


Fig. 1. Input-output model for phenol formaldehyde sand mould process

The experiments were conducted according to American Foundry Society (AFS) standard in the metal casting industry for the design matrices of central composite (refer Appendix A). The samples are prepared by mixing the appropriate grain fineness number silica sand,amount of resin and hardener in sand muller as per the design matirix ,using standard rammer and tubes ,sand samples of 5cms diameter and 5cms height are made. The resin used for experimental study is phenol formaldehyde with density 1.115gms/cm3 and kinematic viscosity 38.85centistokes and absolute viscosity is 43.31775 centipoise. The hardener used is poly-toulene sulphonic acid with density 1.227gms/cm^3 and kinematic viscosity is 9.95 centistokes and 12.20865 centipoise. Three replicates were considered for each set of input parameters and the corresponding outputs were measured. The average of three replicates of output values was used to develop model building and testing. The individual and combined effects of factors were tested for significance towards mould hardness and permeability. The models established were validated statistically to check their adequacies using ANOVA. The practical significance of the models developed was tested with the help of ten random experimental conditions (refer Appendix B). The data collected for two outputs, namely, mould hardness and permeability, is described as follows,

2.1. Response Measurement: Permeability and Mould Hardness

The mould hardness and permeability samples (5 cm in height and diameter) were prepared for different sand mould conditions as per AFS standard. Digital stop watch recorded the time span required to surpass 2000 CC of air through specimen using a permeability meter (Fig. 2a). The air pressure was recorded with the help of permeability meter. The digital weigh balance was used to record the sample weight.
The mould hardness was measured using mould hardness tester (Fig. 2b) on the samples prepared according to AFS standard.



(a) (b)
Fig. 2. Testing apparatus: a) permeability meter and b) mould hardness

2.2 Optimization: DFA

The optimum values of four input parameters can be determined to locate the extreme values of mould hardness and permeability using DFA. In DFA, each output Y_i is converted first to individual desirability function d_i, whose value lie in the range of 0 to 1 ($0 \leq d_i \geq 1$). Zero dictates a completely undesirable solution and one signify the ideal solution. Permeability and mould hardness are two individual desirability functions affecting the phenol formaldehyde process. The composite desirability (D_o) value is then determined as shown below:

$$D_0 = \sqrt{y_P^{w_1} \cdot y_{MH}^{w_2}} \quad (1)$$

Y_P and Y_H are objective functions utilized for normalization,

$$y_P = \frac{P - P_{min}}{P_{max} - P_{min}}, \quad y_H = \frac{H - H_{min}}{H_{max} - H_{min}} \quad (2)$$

P_{max} is maximum values of permeability; $P_{min}$is minimum values of permeability; H_{max} is maximum values of mould hardness and $H_{min}$is minimum values of mould hardness.

2.2.1 Mathematical formulation for multi-objective optimization

The permeability and mould hardness are two multiple objective functions and have many solutions, which makes the selection of the best moulding sand combinations difficult for foundry personnel. Thereby three different scenarios were considered to solve the said problem. Scenario 1 dealt with assigning equal importance (weight fraction) to two outputs and maximum weight fraction to one output after keeping the other at a minimum weight fraction for both scenarios 2 and 3. w_1f_1, and w_2f_2 were the weight fraction combination with permeability and mould hardness, respectively. The weight fractions were chosen such that the composite weight fraction of all output combinations must be kept equal to one. The resultant composite weighted multiple objective functions for maximization is defined as follows:

Objective function, f_1 = P
Objective function, f_2= H
Maximize F = $w_1f_1 + w_2f_2$

Subject to process variable constraints

$50 \leq A \geq 90$
$1.8 \leq B \geq 2.2$
$0.8 \leq C \geq 1.2$
$60 \leq D \geq 120$

DFA defines the input values that could locate extreme values of outputs through their search mechanism. DFA determines output values of optimum sand mould properties for three different combinations of weight fraction assigned for objective functions. The choice of the best sand mould properties are determined corresponding to the highest composite desirability value obtained.

3. Results and discussions

The experimental input-output data were collected according to the design matrices of central composite. Statistical analysis was conducted to determine both individual and combined input parameter significances on the measured outputs. The adequacy of developed model is checked with the help of ANOVA test. The model was validated for prediction accuracy of each response with the help of 20 random test conditions. Minitab software was used to perform the said task. Response wise analysis was conducted, which is discussed in the subsequent sections.

3.1 Response: Mould Hardness (H)

The non-linear relationship of mould hardness and input variables expressed in uncoded form as shown in Eq. 3.

$$H = 94.5 - 2.416A - 46.9B + 99.4C + 0.606D + 0.01671A^2 + 14B^2 - 45.4C^2 - 0.003266D^2 + 0.0078AB + 0.0391AC + 0.002031AD - 1.56BC - 0.0521BD + 0.0104CD \quad ..(3)$$

Table 2 shows the significant and insignificant terms and coefficient of correlation determined for mould hardness at the 95% preset confidence level. All linear factors, there square terms (except percent of resin) and interaction of a grain fineness number and setting time significantly contribute towards mould hardness. The square term of the percent of resin is insignificant due to the absence of non-linearity. The significance test results were found to be in good agreement with the obtained surface plots shown in Fig. 3 (a-f). The interaction terms (AB, AC, BC, BD, CD) were found to be insignificant indicating simultaneous increase or decrease in both the values of parameters without changing the output value much. The linear, square and interaction terms were found statistically significant for the defined preset confidence level; however, the model failed to make the lack of fit term significant (refer Table 4). Removing insignificant terms from the model derived response equation produced lack of fit term significant, but reduced the prediction accuracy. This might be due to higher estimated F-value in comparison to the tabulated F-value.

The surface plots explain the output behavior to change in input variables between their respective levels. Surface plot analyzes the response behavior when simultaneously two variables are varied after keeping the rest factors at constant middle values. The key points from the obtained surface plots are

1. Increase in grain fineness number showed non-linear (decrease initially and increase rapidly after the mid-values of GFN) relationship when varied with percent of resin, hardener and setting time on mould hardness as shown in Fig. 3a-c.Fine sand grain requires low quantity of resin and hardener and adequate time to undergo polymerization reactions that would help to coat entire sand grains with high mould hardness. GFN impact on mould hardness is comparatively more than that obtained for setting time percent of hardener and percent of resin.
2. The percent of resin showed a linear relation when varied with percent of hardener and setting time on mould hardness (refer Fig. 3d-e). However, setting time and the percent of hardener increase drastically with slight decrease in mould hardness towards the end. This occurred due to low setting time, quantity of resin, and hardener which may not have got activated to undergo polymerization reactions developing strong bonding between the molecules of resin.
3. Increase in hardener content with progressive setting time could increase the mould hardness, though with a slight decrease towards the end (Fig. 3f). Higher hardener content dilutes the resin quantity resulting in over coating of sand grains, which may lead to decrease in the compaction strength of mould hardness.

Table 2.
Results of significance test for mould hardness

Output	Coefficient of correlations		Parameters	
	Including all terms	Without insignificant terms	Significant terms	Insignificant terms
Mould hardness	0.9674	0.9293	A, B, C, D, AA, CC, DD, AD	BB, AB, AC, BC, BD, CD

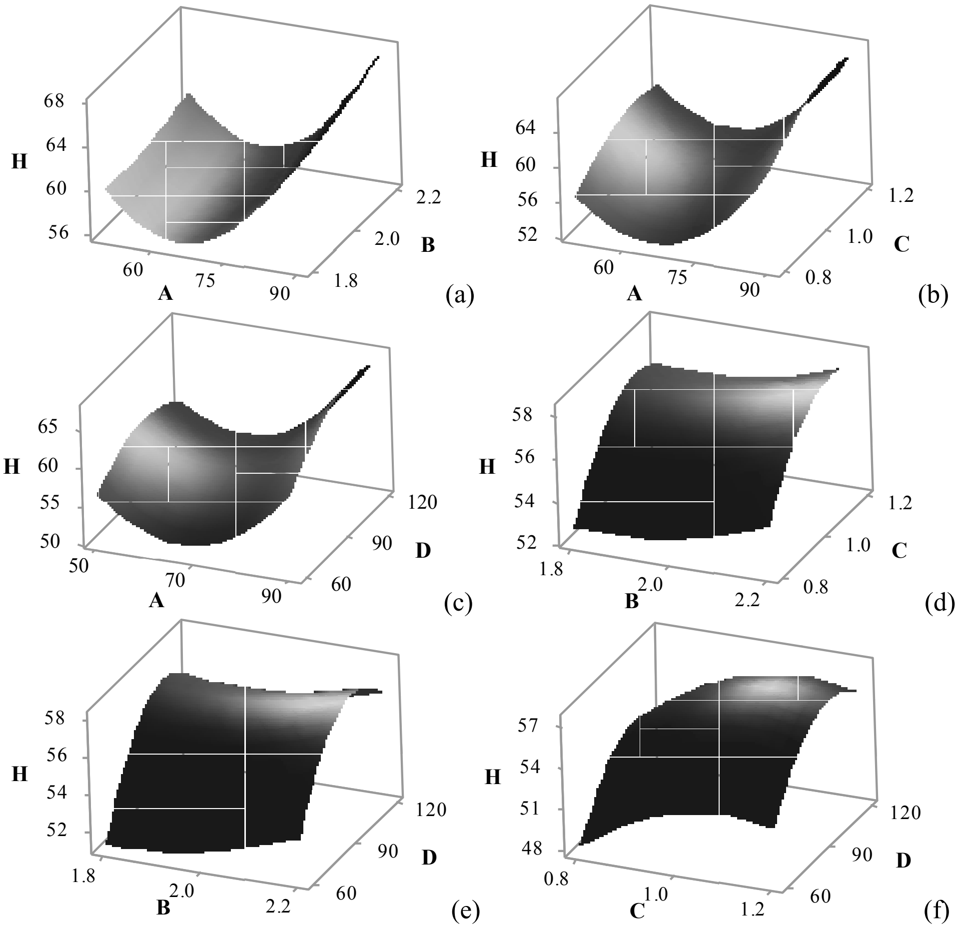


Fig. 3. Surface plots of mould hardness with a) GFN and percent of resin, b) GFN and percent of hardener, c) GFN and setting time, d) percent of resin and percent of hardener, e) percent of resin and setting time, and f) percent of hardener and setting time

3.2 Response: Permeability (P)

The permeability of the moulding sand is expressed as a non-linear function of input variables in uncoded form as shown in Eq.4. The model showed different significant and insignificant terms for response permeability is presented in Table 3.

$$P = 6605 + 87.03A - 8180B - 3876C + 17.42D - 0.6473A^2 + 2215B^2 + 2465C^2 - 0.0016D^2 - 1.0AB + 1.34AC + 0.0194AD - 87BC - 4.33BD - 8.81CD \quad ....(4)$$

Table 3.
Results of significance test for permeability

Output	Coefficient of correlations		Parameters	
	Including all terms	Without insignificant terms	Significant terms	Insignificant terms
Permeability	0.9741	0.9440	A, B, C, D, AA, BB, CC, BD, CD	DD, AB, AC, AD, BC

The statistical significance of input variables on permeability is explained as follows:

1. All linear factors are found statistically significant. GFN, percent of hardener, setting time and percent of resin have arranged in ascending order based on significant importance.
2. The square terms of setting time parameter were found to have a linear relationship with permeability.
3. GFN and percent of hardener were found to be the highest contributor individually, but interaction among them was observed to be insignificant. This indicates the process is complex and highly non-linear.

High values of setting time associated with low quantities of resin and hardener, when GFN kept at middle values always resulted in better permeability. Higher setting time provided adequate time to develop cohesive bonding between the hardener and resin layers of sand grains resulting in uniform round grains, thus mould has been shown to allow the escape of gas easily. The setting time interaction with percent of hardener is comparatively higher than that obtained with percent of resin. Low permeability value was obtained when all factors set at their respective middle values.

The model determined all linear, quadratic, interaction and lack of fit terms to be significant for the preset 95% confidence level with good correlation coefficient (refer Table 4). Thereby, the model is statistically adequate and can make better predictions with random test cases.

Table 4.
ANOVA test results for mould hardness and permeability

Response		Permeability				Mould hardness			
Source	DF	Adj. SS	Adj. MS	F	P	Adj. SS	Adj. MS	F	P
Model	14	346659	24761	32.30	0.000	491.287	35.092	25.40	0.000
Linear	4	97434	24358	31.78	0.000	326.729	81.682	59.12	0.000
Square	4	190600	47650	62.16	0.000	138.698	34.675	25.10	0.000
Interaction	6	58625	9771	12.75	0.000	25.859	4.310	3.12	0.044
Error	12	9199	767			16.579	1.382		
Lack of fit	10	9182	918	110.19	0.009	14.037	1.404	1.10	0.565
Pure error	2	17	8			2.542	1.271		
Total	26	355858				507.866			

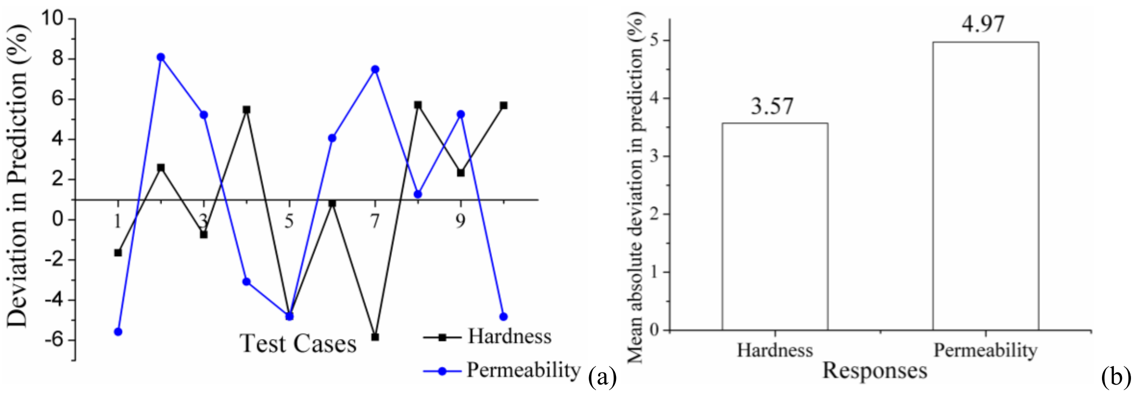


Fig. 4. Prediction performances for 10 experimental conditions: a) percent deviation and b) average absolute percent deviation

3.3 Testing Model Prediction Performances

In the earlier section, the collected experimental input-output data were analyzed and complete insight of detailed information of a process was provided. The practical significance of the developed models was tested for 10experimental cases for each output separately. The input variables lying within their respective levels were generated randomly and the outputs evaluated the model prediction accuracy.

3.3.1 Responses: H and P

Ten sets of experiments were conducted to record the data of mould hardness and permeability for the randomly generated test conditions (refer Appendix B). Fig. 4a shows the values of percent deviation in prediction of permeability and mould hardness. The percent deviation value varies on both positive and negative sides of the reference zero line in the ranges of -5.84 and +5.72 for mould hardness and -5.58 and +8.10 for permeability, respectively. Fig. 4b shows the absolute deviation in the average prediction of 10experimental conditions, which was equal to 3.57% for mould hardness and 4.97% for permeability.

3.4 Multiple Objective Optimization

The try-error method of sand moulding process optimization subjected to input factor constraints is considered as inefficient due to the existence of complex non-linear relations. The mathematical objective functions have been derived for mould hardness and permeability was expressed as a non-linear function of input variables separately. The high and low constrained input values helped to locate the extreme values of both mould hardness and permeability. Multiple objective functions have many solutions and the best choice of moulding condition for the desired mould hardness and permeability is always considered difficult for a foundry personnel. Hence, three case (scenario) studies with different combination of weight fraction was assigned to each objective function and composite desirability value for the same was determined. Three different scenarios were selected such that scenario 1 dealt with assigning equal weight fractions for each objective function, scenarios 2 and 3 used maximum weight fraction for one output function after maintaining the rest at low weight. DFA was used to search the desired high permeability and mould hardness under subjective input variable constraints of the developed non-linear objective functions of the phenol formaldehyde process. The DFA prediction performance was compared among themselves with different case studies by determining the composite desirability value. The value with the highest composite desirability defined the optimal sand mould condition for a process (Table 5).

The DFA determined the input parameter condition that favors the optimized sand mould properties with the highest desirability values. The present work recommends scenario 2 (permeability, weight fraction = 0.9 and hardness, weight fraction = 0.1) as it can yield better sand mould properties; in addition its composite desirability value was found to be greater than that obtained for the rest of the case studies considered. The two most significant interaction factors for each output were plotted after keeping the rest at constant middle values. GFN showed a major impact on permeability compared to that obtained for curing time (Fig. 5a). Mould hardness tends to improve with increase in resin-to-hardener ratio and curing time as shown in Fig. 5b. However, further increase in hardener content with progressive setting time diluted the resin quantity resulting in over coating of grains leading to a slight decrease in mould hardness towards the end. The average deviation in percent prediction determined after conducting actual experiments (refer Table 6) was found to be equal to 3.7. Thus, significant scope exists for determining optimum sand mould properties responsible for a set of input parameters.

Table 5.
Optimized sand mould properties and corresponding input conditions

Process variables and sand mould properties	Sand mould conditions and properties		
	Scenario 1: $W_1 = W_2 = 0.5$	Scenario 2: $W_1 = 0.9$, $W_2 = 0.1$	Scenario 3: $W_1 = 0.1$, $W_2 = 0.9$
Grain fineness number	83.5	81.1	90.0
Percent of resin	2.20	2.20	1.80
Percent of hardener	1.20	1.20	1.20
Setting time	96.6	101.2	119.4
Permeability	582.8	620.2	411.0
Mould hardness	63.6	62.2	67.3
Composite desirability (D_o)	0.9165	0.9816	0.9678

Table 6.
Confirm experiments for an optimized sand mould condition of mould hardness and permeability

Exp. No.	Input parameters				Moulding sand properties	
	A	B	C	D	Mould hardness	Permeability
1	81	2.2	1.2	101	65	648

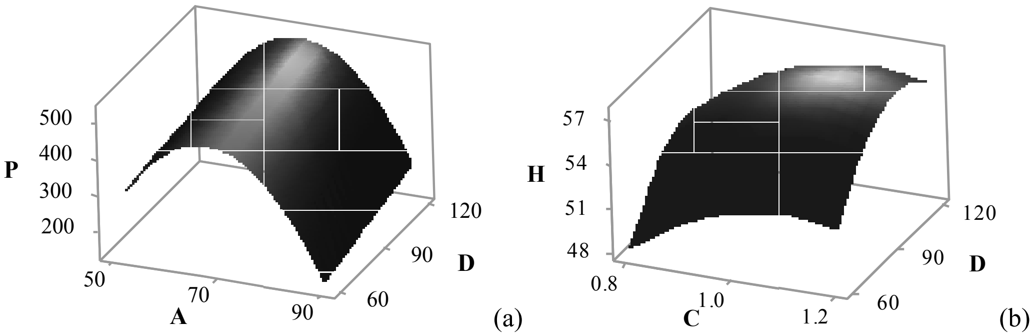


Fig. 5. Surface plots with highest interaction factor effects for the outputs: a) permeability, and b) mould hardness

5. Conclusion

Statistical modeling and optimization of phenol formaldehyde based sand moulding process was carried out using DOE. The experiments were conducted according to the matrices of central composite design. The permeability and mould hardness were measured for each experimental condition. The significance of individual and combined factor effects was determined for both outputs separately. Surface plots are drawn to explain the behavior of outputs with variation in individual parameters. The prediction accuracy for the practical usefulness in metal casting industries was tested for the derived response equation with ten random experimental cases. The optimum values of permeability and mould hardness were determined for a single input variable combination using DFA. The confirmation experiments were also conducted for an optimized sand mould condition. The key observations made from the present experimental modeling and optimization area as follows:

1. Grain fineness number determined as the most significant parameter that could influence both mould hardness and permeability.
2. The square terms of grain fineness number and percent of hardener were significant indicating a strong non-linear relationship with both mould hardness and permeability. Setting time was found to have a linear relationship with permeability, whereas a non-linear relationship with mould hardness.
3. The average absolute deviation to predict 10 randomly generated experimental conditions resulted in 3.56% for mould hardness and 4.97% for permeability. Thereby the present work is more useful for foundry persons to predict the outputs for known combinations of inputs.
4. The confirmation experiments conducted for the optimized sand mould conditions determined by the DFA produced better permeability and mould hardness properties. The absolute deviation in prediction with experimental values of permeability and mould hardness was 4.3%.
5. The determined optimized combination of mould hardness and permeability will help foundry personnel to reduce trial experiments, material waste and advice from foundry experts.
6. The developed model will help the foundry industry to obtain better sand mould properties without the requirement of additional experiments.

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Appendix A:
Central composite design matrices for experimental input-output data collection

Sl.	Input parameters				Outputs	
No	A	B	C	D	Mould hardness	Permeability
1	50	1.8	0.8	120	54.00	510
2	50	1.8	1.2	120	58.00	490
3	70	2	1	60	51.00	460
4	90	2.2	0.8	120	64.25	450
5	50	1.8	1.2	60	55.00	460
6	50	1.8	0.8	60	53.50	300
7	70	2	0.8	90	54.00	600
8	90	2	1	90	66.75	185
9	70	2.2	1	90	58.50	600
10	90	2.2	1.2	120	67.00	410
11	50	2.2	0.8	60	54.00	440
12	90	1.8	1.2	120	67.25	400
13	70	2	1	90	55.50	490
14	90	2.2	1.2	60	62.00	465
15	50	2.2	0.8	120	54.50	500
16	70	2	1	120	57.25	540
17	90	1.8	0.8	120	62.75	400
18	70	2	1	90	54.50	485
19	90	1.8	0.8	60	55.25	194
20	50	2	1	90	60.75	300
21	70	2	1.2	90	56.50	600
22	70	1.8	1	90	56.75	580
23	90	1.8	1.2	60	61.00	405
24	50	2.2	1.2	60	58.00	620
25	50	2.2	1.2	120	59.00	460
26	90	2.2	0.8	60	58.50	270
27	70	2	1	90	56.75	490

Appendix B:
Input-output data for test cases

Sl.	Input factors				Responses	
No	A	B	C	D	Permeability	Mould hardness
1	60.0	1.8	1.0	95	56	405
2	55.0	2.0	0.9	75	57	310
3	54.5	2.2	0.8	60	52	465
4	85.0	2.1	1.1	115	68	274
5	90.0	2.1	1.2	110	65	215
6	75.0	2.0	1.0	85	58	380
7	75.0	1.9	0.8	80	50	460
8	80.0	1.8	0.9	120	62	480
9	65.0	1.8	1.2	98	58	605
10	75.0	2.0	1.1	90	62	385