# Application of Response Surface Methodology for Modeling the Properties of Chromite-based Resin Bonded Sand Cores

B. Surekha, D. Hanumantha Rao, G.Krishna Mohana Rao, Pandu R Vundavilli and

M.B. Parappagoudar

*Abstract*—Resin bonded sand cores are increasingly used in applications where high dimensional accuracy is required. The quality of the cast products produced using this system mainly depends on the properties of the core, namely compression strength, shear strength, tensile strength and permeability, which in turn depends on the process parameters, such as amount of resin, amount of hardener, number of strokes and curing time. The relationships of these input parameters with the properties of the core are complex in nature. In the present paper an attempt has been made to establish the said input-output relationships with the help of response surface methodology. A three level central composite design is utilized to conduct the experiments. Surface plots are used to study the effects of amount of resign, amount of hardener, number of strokes and curing time on the responses. Moreover, analysis of variance test has been conducted to determine the statistical adequacies of the developed models. The prediction accuracy of the non-linear models have been tested with the help of twenty test cases, and found reasonably good accuracy.

***Keywords—***Chromite sand, resin bonded sand core, central composite design, regression analysis.

## I. Introduction

THE cold box process is most widely used to produce castings of high density. The moulding/core sand is prepared at room temperature and consists of sand, resin (binder) and the hardener. The use of resin as binder in making cores/moulds will result in castings with better surface finish and high dimensional accuracy. It is important to note that the mechanical strength of resin bonded core depends on the adhesive force between the resin binder to sand grains and the cohesive force of the resin film itself. The draw back with resin bonded sand core/mould is that it takes long time for curing reaction to take place for the binder to become effective and allow formation of the mould. The important constituents of chromite-based resin bonded sand core system are the chromite sand, resin and hardener.

Limited work had been reported in literature on modeling and analysis of the resin-bonded sand core system. However, some researchers identified a wide variety of chemical binders for making cores and moulds [1]. Experiments were conducted by researchers [2], to study the effect of various organic binders, such as urea formaldehyde, linseed oil and phenol formaldehyde resins with different catalysts. It was observed that modified phenol formaldehyde had shown superior performance when compared with other resins. Shetty et al. [3] used molasses as binder and calcium oxide as hardener for sand mould system. They performed some studies on the properties of self setting sand. In [4], the process performance was improved by using a new solvent system based on methyl esters of vegetable oils. A considerable reduction in volatile emissions was observed. Triphenyl phosphate, as an additive was added to cold setting furan resin in [5] to enhance the average tensile strength of the resin-bonded sand system. It was observed that both the gas evolution and deformability of cold-setting resin were improved. Howden [6] studied the application of chromite sand in steel foundries. It was identified that the double skin defect of chromite sand could be due to binder content, drying procedure, pouring speed, pouring temperature and the oxygen activity with the liquid steel.

A new phenol formaldehyde resin binder systems which can react with carbon dioxide gas was developed in [7]. The compression strength of the carbon dioxide cured resin bonded sand system was found to be increased with time. Zhang et al. [8] analyzed the reasons for strength loss mechanism of phosphate bonded sand mold/core with the help of electron probe x-ray mocroanalyzer. The results showed that the addition of magnesium enhanced hydroscopy resistance of phosphate membrane to a large extent. Experimental determination of thermo-mechanical properties of cold-box

B. Surekha is a Research Scholar at JNTU Hyderabad and is with the Department of Mechanical Engineering of Gandhi Engineering. College, Bhubaneswar, Odissa, India-752054 (Phone:+91-9776220902; e-mail: surekha_vundavilli@yahoo.co.in).

D. Hanumantha Rao is with the Department of Mechanical Engineering of Matrusri Engineering College, Hyderabad, A.P, India – 500059(e-mail:dharwada.rao@gmail.com).

G.K.M. Rao is with the Department of Mechanical Engineering of JNTU Hydearabad, A.P, India – 500085 (e-mail: kmrgurram@gmail.com).

Pandu R. Vundavilli is with the School of Mechanical Sciences of IIT Bhubaneswar, Bhubaneswar, Orissa, India – 751013 (e-mail: pandu@iitbbs.ac.in).

M.B. Parappagoudar is with the Department of Mechanical Engineering of Chhatrapati Shivaji Institute of Technology, Durg, CG, India – 491001 (e-mail: maheshpg@gmail.com).

sand during the solidification of the casting was studied by researchers [9]. The experimental results at room temperature showed a strength differential effect in tension and compression, where compression strength was found to be much higher. In [10], the authors explained the uses of phenolic resin as binder in the sand mold. They had also explained the chemistry and core making process using phenolic resin. It is interesting to note that instead of conducting experiments, some researchers had used the simulation software to study the physical system.

Experimental and numerical study of bonded sand/air two-phase flow in phenolic urethane amine process was presented by Bakhtiyarov and Overfelt [11] with the help of a square core box. The barometric readings were used to generate the contour maps of the pressure distributions inside the core box. A computer controlled system for the measurement of pressure and flow rates inside the core box was developed. Moreover, the time step model of simulation in solidification process was presented in [12]. A formula of time step in solidification was derived based on conservation of energy, which was compared with the results of numerical experiments. A 20% computational efficiency in the simulation of solidification process was obtained. In [13], a finite element analysis package was used to study the solidification process of cast iron in resin bonded sand mould system. To verify the model, molten grey cast iron with 1300oC temperature was poured in to the resin bonded sand mould. The solidification temperature was found to be high at the mold wall and reasonably low at the sprue. It is important to note that several researchers were tried to establish the analytical relationships between the process parameters and the responses. However, it could be difficult to establish the said input-output relationships due to the inherent complexity of the process. Moreover, the statistical modeling using Design of Experiments (DOE) [14] was proven to be an effective tool for studying the complex relationships of number of independent variables on response factor of a particular process.

Statistical design of experiments [15] and Taguchi method [16, 17] were used to study and control the properties, and behavior of different sand systems. The compressive strength of a molasses-cement sand system was modeled with the help of non-linear regression equation [18]. Percentage of molasses and cement were used as inputs and the experiments were planned according to Central composite design of experiments. The linear and non-linear modeling of green sand mould system [19] and cement-bonded sand mould system [20] was carried out by Parappagoudar et al. by utilizing statistical regression analysis. Moreover, statistical modeling of green sand mould using response surface methodology was reported in [21]. The statistical regression models correlated bulk density, compactability, permeability and compression strength to the set of inputs, like percentage of bentonite, of water, curing time and the environment of the specimen preparation. Bast et al. [22] used a full factorial design of experiments to formulate a linear regression equation for the adhesion and cohesion force of the mould. In [23], design of experiments was used to establish the multiple linear regression analysis of quartz-based resin bonded sand mould system.

The present work aimed at utilizing design of experiments (DOE) and response surface methodology (RSM) to establish complex input-output relationships in chromite-based resin bonded moulding/core sand systems. Experiments have been conducted to analyze the complex effects of input variables, such as percentage of resin, percentage of hardener, number of strokes (degree of ramming) and curing time on mould properties, namely compression strength (CS), tensile strength (TS), shear strength (SS) and permeability (P). ANOVA test has been conducted to test the statistical adequacy of the developed models. Moreover, the accuracy of the developed non-linear regression models for all the responses has been tested with the help of test cases.

## II. METHODOLOGY USED IN THE PRESENT WORK

The methodology to study the influence of process parameters and to establish non-linear input-output relationships of a chromite-based resin bonded sand core system has been explained in the following steps.

### *A. Identification of Important Process Parameters and Their Levels*

The moulding/core sand mixture used consists of three ingredients, namely chromite sand, resin – phenol formaldehyde and the hardener – tetrahydropthalic anhydride.

*Sand – Chromite Sand*

Sand is the major ingredient i.e. about 95 to 98% of the total moulding/core sand mixture consists of sand. Hence, the type and characteristics of sand play major role in developing the important properties. Chromite sand is dense, weighing 160 lbs per cubic feet compared to silica sand (weighing 98 lbs per cubic feet) of same screen distribution. It is not easily wetted by molten metal and is found to be highly refractory with melting point around 2090 degree centigrade. The chromite sand can be used to cast metals of high density and melting point, where the use of silica sand may result in defects like sand fusion. The Chromite sand replace Zircon sand, since the cost is low.

*Resin – Phenol Farmaldehyde*

In the present work phenol formaldehyde is used as the binder. Phenol formaldehyde resin is a highly cross linked thermosetting material that is produced by poly condensation of phenol and formaldehyde in the presence of either acid or basic catalyst. The ratio of phenol to formaldehyde determines the grade Phenol is a crystalline solid, melting at 39 degree centigrade. Formaldehyde is a gas but the commercial application product is 37% solution of formaldehyde gas in water. The amount of resin required to develop good strength depends grain fineness number and grain shape. Finer grains need more resin due to increased surface area.

*Hardener – Tetrahydropthalic anhydride*

Phenol formaldehyde reacts with the hardener tetrahydropthalic anhydride over a period of time and develop strong bonding strength with sand particles. Phthalic anhydride, the anhydride form of phthalic acid, is produced by the oxidation of orthoxylene and naphthalene. Its wide application is based on the orthorelated carboxylic acid groups and their dehydration is highly reactive with broad processing conditions to produce various downstream products. Anhydride is a compound formed by the abstraction of a molecule of water from a substance. Organic anhydrides are formed by the condensation of original acids. Anhydrides are more reactive than the parent acids and typically not target molecules. The addition of hardener can be increased or decreased to the desired level to get fast or slow curing. The variations in temperatures, humidity etc. can be adjusted through curing rate, so that the desired bench life of the sand mix and strip time can be obtained [24].

Percentage of resin, percentage of hardener, number of strokes and curing time has been considered as independently controllable process parameters with significant contribution on mould/core properties. The working ranges of the input parameters are determined by consulting the experts from foundry and literature. Table 1 shows the ranges of the input process parameters used for conducting the experiments.

Table 1: The Process parameters and their chosen levels

| Parameter | Levels | | |
|---|---|---|---|
| | Low (-1) | Medium (0) | High (+1) |
| % Resin | 1.5 | 2.0 | 2.5 |
| % Hardener | 30 | 40 | 50 |
| Number of strokes | 3 | 4 | 5 |
| Curing time | 60 | 80 | 100 |

Moreover, compression strength, shear strength, tensile strength and permeability of the core are considered as responses for the chromite-based resin bonded sand core system. The block diagram showing the input-output relationships of the chromite-based resin bonded sand system is shown in Fig. 1.

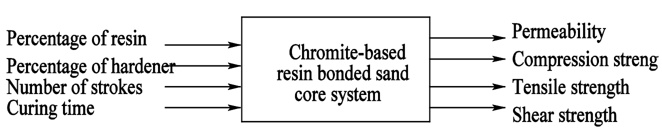



Fig. 1: Input-output model of the chromite-based resin bonded sand system.

*B. Development of Design Matrix*

Central composite design is one of the popular and common method used to develop the non-linear model. The planning of the experiments is carried as per the DOE. The design matrix, for four input parameters consists of 27 sets of experiments, comprising of 16 factorial experiments with 3 center points and 8 star points. Therefore, the 27 experimental runs allowed the estimation of linear, square and two-way interaction effects of the input parameters. Moreover, three replicates are considered for each combination of the input variables and test cases.

*C. Conducting Experiments*

(a)Sand ramming machine

(b) Universal sand testing machine

(c) Permeability tester

Fig. 2: Schematic diagram showing the experimental devices.

Experiments have been conducted to test the properties of chromite-based resin bonded sand core system. The cores are prepared with the help of chromite sand, resin and hardener. The type of resin and hardener used in the present study is phenol formaldehyde ($C_7H_6O_2$) and tetrahydrophthalic anhydride ($C_8H_8O_3$), respectively. The grain fineness number (GFN) of the chromite sand that was obtained from the sieve analysis test has been found to be equal to 41. Standard procedure has been used to prepare the test specimens. Specified quantity of hardener is added to the chromite sand and mixing is done uniformly. Then the required quantity of resin is added to the sand-hardener mixture and mixed it properly, so that the reaction product of resin and hardener is coated to sand particles uniformly. The prepared sand is then poured in the core box and rammed with the help of ramming machine (refer to Fig. 2(a)) to acquire the desired compaction.

Bonding occurs between chromite sand particles over a period of time due to the reaction between the resin and hardener. Then the prepared core is kept a side for the amount of time, which is equal to the curing time specified in the design matrix to acquire the bonding strength. The compression, shear and tensile strengths are measured using universal sand testing machine (refer to Fig. 2(b)) and the permeability of the core is measured with the help of permeability meter (refer to Fig. 2(c)). The experiments are conducted as per planning of central composite design (refer to Appendix-A). The test specimens shown in Fig. 3 are prepared as per the conditions specified in the central composite design matrix.

Fig. 3: Schematic diagram showing the specimens prepared for testing.

Experiments are conducted to determine compression, tensile, shear strengths and permeability for the cores produced with different combinations of the variables.

*D. Developing Non-linear Model using Response Surface Methodology*

The response function representing the properties, such as compression, tensile, shear strengths and permeability number of chromite-based resin bonded sand core can be expressed as a function of input parameters, namely percentage of resin, percentage of hardener, number of strokes and curing time of the core system. A response surface is a graphical representation of the relationships between the response and a number of factors. The second order polynomial used to represent the response surface for *k* factors can be represented as

$$y = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{\substack{i=1 \\ i \neq j}}^{k} b_{ii}\, x_{ii}^2 b_2 + \sum_{i,j=1}^{k} b_{ij} x_i x_j \quad (1)$$

The above response surface contains linear terms $x_1, x_2, \ldots, x_k$, square terms $x_1^2, x_2^2, \ldots, x_k^2$, and interaction terms $x_1x_2, x_1x_3, \ldots, x_{k-1}x_k$. The resulting polynomial for four factors can be expressed as

$$y = b_0 + b_1 A + b_2 B + b_3 C + b_4 D + b_{11} A^2 + b_{22} B^2 + b_{33} C^2 + b_{44} D^2 + b_{12} AB + b_{13} AC + b_{14} AD + b_{23} BC \; b_{24} BD + b_{34} CD \quad (2)$$

where $b_0$ is free term of the regression equation, $b_1$, $b_2$, $b_3$ and $b_4$ are the coefficients of linear terms, $b_{11}$, $b_{22}$, $b_{33}$ and $b_{44}$ represent the coefficients of quadratic terms and $b_{12}$, $b_{13}$, $b_{14}$, $b_{23}$, $b_{24}$ and $b_{34}$ are coefficients of interaction terms.

*E. Determining the Adequacy of the Developed Models*

The non-linear regression model will be developed using the data collected as per the central composite design. The effect of individual parameters and their interaction terms are examined by conducting a significance test. The adequacies of the models are tested with the help of Analysis of variance (ANOVA) technique. Surface plots are used to understand the relationships of process parameters and their interaction with responses. Further, they are utilized to study the contribution of process parameters. MINITAB software is used for the said purpose. The prediction accuracy of the models has been tested by passing twenty experimental test cases.

## III. RESULTS AND DISCUSSION

This section discusses the non-linear regression models developed for chromite-based resin bonded sand core system using MINITAB software.

*A. Mathematical Models and Statistical Analysis*

The experimental data obtained from chromite-based resin bonded sand core has been used to develop non-linear regression models. Further, the analysis of the models is performed through ANOVA test and surface plots for the responses – permeability, compression strength, tensile strength and shear strength

*Response – Permeability*

Equation (3) shows the non-linear model expressed as a function of input process parameters (in coded form), that represents the permeability of the chromite-based resin bonded sand core system.

$$P_{CCD} = 114.058 + 4.727*A + 6.747*B - 5.131*C - 0.758*D + 0.693*A^2 + 22.775*B^2 + 2.391*C^2 + 2.967*D^2 + 6.713*A*B - 3.130*A*C - 2.654*A*D + 5.154*B*C - 9.362*B*D - 5.385*C*D \quad (3)$$

To examine the effect of various input parameters and their interaction terms on permeability, a significance test (refer to Table 2) has been conducted. The term 'Coef' in Table 2 represents the coefficients used in equation (3) for showing the relationship between the input parameters and the response. The term 'SE Coef' indicates the standard error for the estimated coefficient, which measures the precision of the estimate. The value of the standard error represents the precision of the coefficient. The 'T' value is obtained as the ratio of corresponding value under coefficient and standard error. The 'P' value is the minimum value for a preset level of significance at which the hypothesis of equal means for a given factor can be rejected.

Table 2: Results of the significance test for the non-linear model of permeability

| Term | Coef. | SE | T | P |
|---|---|---|---|---|
| constant | 114.05 | 0.9775 | 116.679 | 0 |
| A | 4.727 | 0.6252 | 7.560 | 0 |
| B | 6.747 | 0.6252 | 10.791 | 0 |
| C | -5.131 | 0.6252 | -8.206 | 0 |
| D | -0.758 | 0.6252 | -1.213 | 0.229 |
| $A^2$ | 0.693 | 1.6542 | 0.419 | 0.677 |
| $B^2$ | 22.775 | 1.6542 | 13.768 | 0 |
| $C^2$ | 2.391 | 1.6542 | 1.446 | 0.153 |
| $D^2$ | 2.967 | 1.6542 | 1.794 | 0.077 |
| AB | 6.713 | 0.6632 | 10.123 | 0 |
| AC | -3.130 | 0.6632 | -4.721 | 0 |
| AD | -2.654 | 0.6632 | -4.003 | 0 |
| BC | 5.154 | 0.6632 | 7.772 | 0 |
| BD | -9.362 | 0.6632 | -14.118 | 0 |
| CD | -5.385 | 0.6632 | -8.120 | 0 |

As the 'P' values of A, B, C, $B^2$, AB, AC, AD, BC, BD and CD are found to be less than 0.05 (corresponding to 95% confidence level), these factors are considered to make significant contribution on the response – permeability. Moreover, the terms D, $A^2$, $C^2$ and $D^2$ are found to be non-significant as their P values are found to be more than 0.05. Thus, the relationship of percentage of resin and number of strokes are having only linear relationship with permeability. This can be observed from the figures 4(a), (b), (c), (d) and (f). Moreover, both the linear and non-linear terms of curing time are found to be non-significant. However, it is interesting to know that, its interaction with all the factors is found to be significant.

The following observations are drawn from the above surface plots for the response - permeability.

1. Fig. 4(a) shows the effects of variation of percentage resin and hardener on permeability. It was observed that the permeability has shown a linear variation with the increase in percentage of resin, whereas the permeability is found to be increased drastically with the increase in percentage of hardener. This may be due to the reason that increases in percentage of resin and hardener results in more rounded grains, which leaves more radial space between the grains.
2. Increase in percentage of resin has shown a linearly increasing permeability. The reason for this same as the one explained above. Moreover, the increase in number of strokes has reduced the permeability (Fig. 4(b)). It may be due to the reason that increase in number of strokes will result in higher compaction and lower permeability.
3. Fig. 4(c) has shown a similar trend as that of the Fig. 4(b). With the increase in percentage resin the permeability is seen to be increased, and with the increase in curing time the permeability is found to be decreased. This may be due to the fact that long curing time helps in the formation of cohesive bonding between the resin layers of the sand grains.
4. Permeability has shown a parabolic variation with minimum at the mid value of percentage hardener (Fig. 4(d)).
5. Permeability is found to be increased with increase in percentage of resin, but there is a decrease in permeability with increase in curing time (Fig. 4(e)). The reason is same as the one explained above.
6. Both the number of strokes and curing time would reduce the permeability when they are increased from their respective lower levels to higher levels (Fig. 4(f)). This may be due to the higher compaction results from increasing the number of strokes and more cohesive bonding due to long curing time.

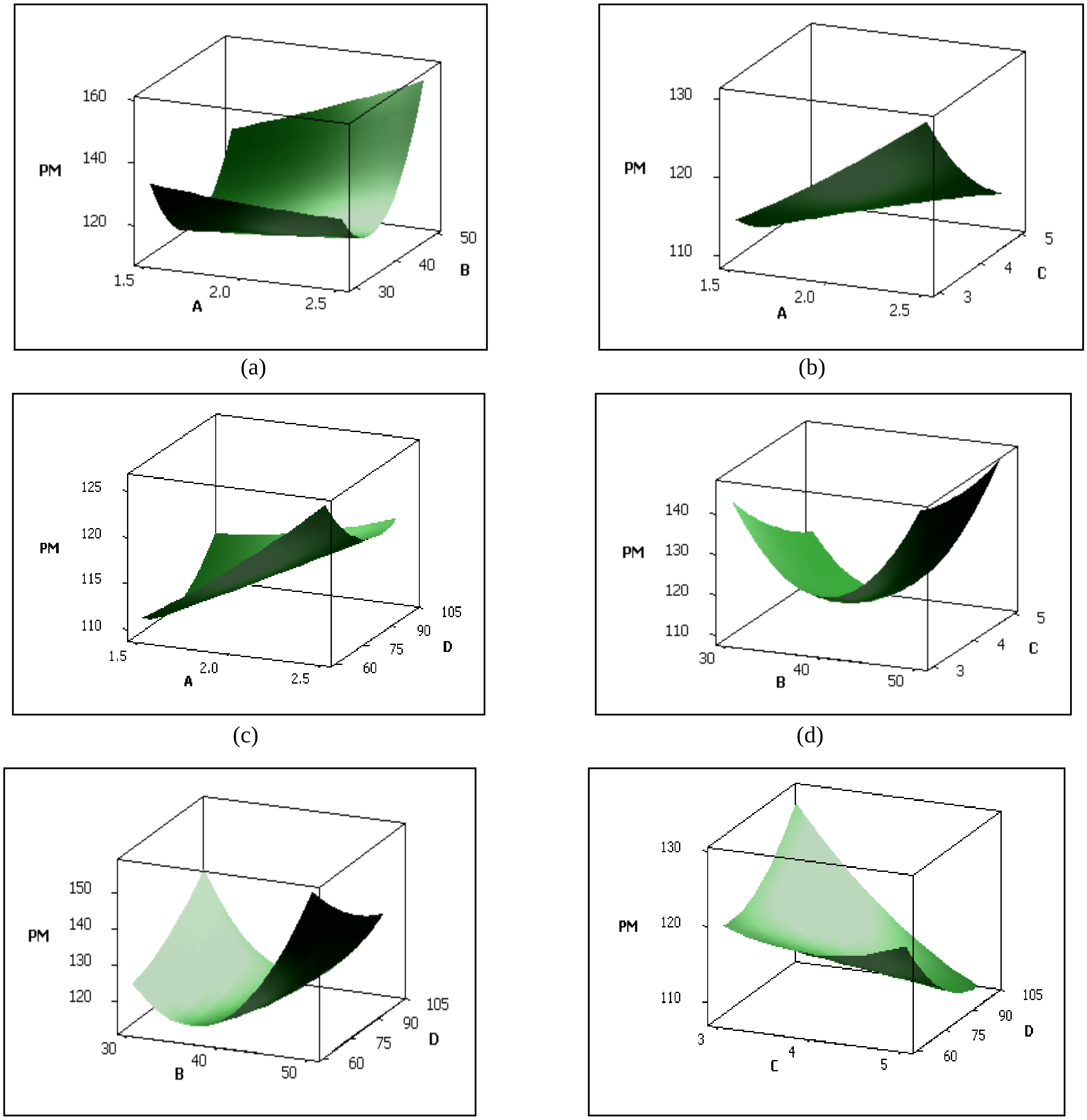



Fig. 4: Surface plots of permeability with: (a) Percentage of resin and hardener (b) percentage of resin and number of strokes (c) percentage of resin and curing time (d) percentage of hardener and number of strokes (e) percentage of hardener and curing time (f) number of strokes and curing time.

However, it is to be noted that, the range of variation in permeability with different parameters and their combination is not found to be much. In order to obtain the non-linear regression equation in un coded form, the input parameters are converted with the following relationship.

$$A = \frac{X_1 - 2}{0.5} \quad B = \frac{X_2 - 40}{10} \quad C = \frac{X_3 - 4}{1} \quad D = \frac{X_4 - 80}{20}$$

where A, B, C and D represent the input parameters, such as percentage of resin $X_1$, percentage of hardener $X_2$, number of strokes $X_3$ and curing time $X_4$, respectively in the coded form. The response equation in un-coded form can be written as shown in Eqn. (4).

$$P_{CCD} = 414.318 - 9.06117*X_1 - 18.5473*X_2 - 10.8180*X_3 + 2.25541*X_4 + 2.77119*X_1^2 + 0.227748*X_2^2 + 2.3913*X_3^2 + 0.0074182*X_4^2 + 1.3427*X_1*X_2 - 6.26096*X_1*X_3 - 0.265431*X_1*X_4 + 0.515431*X_2*X_3 - 0.0468114*X_2*X_4 - 0.269232*X_3*X_4 \quad (4)$$

Table 3 shows the results of ANOVA performed for testing the significance of the factors on permeability. The term ‘DF’ in Table 3 represents the degree of freedom that indicates the number of terms that will contribute to the error in prediction. Moreover, the terms ‘Seq. SS’ and ‘Adj. SS’ gives the sum of squares for each term and sum of squares after removing the insignificant terms, respectively. Similarly, the ‘Adj. MS’ is the mean square obtained after removing the insignificant terms from the response. The ‘F’ value of regression is used to test the hypothesis.

Table 3: Results of ANOVA for the response - permeability

| Source | DF | Seq SS | Adj. SS | Adj. MS | F | P |
|---|---|---|---|---|---|---|
| Regression | 14 | 28137.0 | 28137.0 | 2009.79 | 95.21 | 0 |
| Linear | 4 | 5117.2 | 5117.2 | 1279.31 | 60.60 | 0 |
| Square | 4 | 13173.6 | 13173.6 | 3293.39 | 156.01 | 0 |
| Interaction | 6 | 9846.2 | 9846.2 | 1641.04 | 77.74 | 0 |
| Residual error | 66 | 1393.2 | 1393.2 | 21.11 | | |
| Lack-of-fit | 10 | 739.2 | 739.2 | 73.92 | 6.33 | 0 |
| Pure error | 56 | 654.0 | 654.0 | 11.68 | | |
| Total | 80 | 29530.2 | | | | |

It is important to note that all the terms are found to be significant on permeability as the value of ‘P’ is found to be less than 0.05. Moreover, the coefficient of correlation for this model is seen to be equal to 0.953. The results indicate that the developed non-linear regression model based on central composite design is statistically adequate for making predictions.

*Response – Compression Strength*

The mathematical relationship given in Eqn. (5) shows the non-linear relationship of compression strength of chromite-based resin bonded sand core with the input process parameters in coded form.

$$CS_{CCD} = 1246.72 + 191.80*A + 158.45*B + 8.24*C + 70.42*D - 244.86*A^2 + 348.18*B^2 - 21.09*C^2 - 57.48*D^2 + 50.77*A*B + 28.73*A*C - 7.42*A*D - 27.51*B*C - 121.63*B*D + 34.77*C*D \quad (5)$$

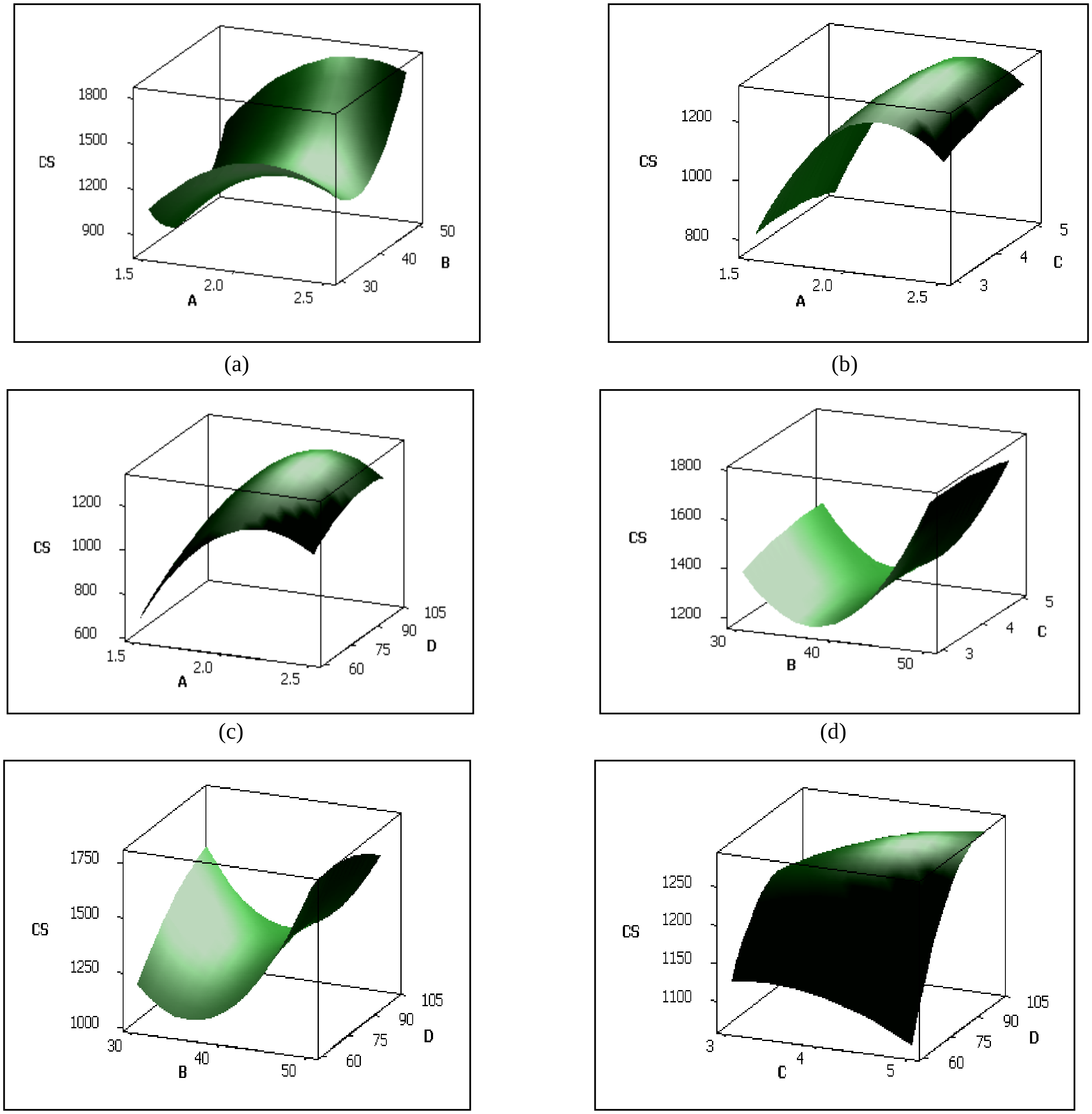
The significance test shows that the linear term C, square terms $C^2$, $D^2$ and interaction terms AC, AD, BC are found to make non-significant contributions on compression strength as their values are seen to be more than 0.05. The surface plots are also drawn for the response – compression strength, and the following observations are drawn.

1. The combined increase in percentage of resin and of hardener is seen to increase the compression strength (refer to Fig. 5(a)). This may be due to the reason that lower quantity of hardener may not be sufficient to activate all resin available resulting in some unused resin.
2. From Fig. 5(b), compression strength is found to increase initially with percentage of resin, reaches maximum and decreases slightly at the end. This might be due to the increased thickness of coating of resin on sand grains.
3. Compression strength is found to increase rapidly with percentage of resin and seen to increase steadily with the curing time (Fig. 5(c)). This may be due to the reason that long curing time allowed the amount of resin to form more bonding with the surrounding grains.
4. The increase in percentage hardener increases the compression strength in a non-linear manner, whereas the compression strength varies linearly with the increase in number of strokes (Refer to Fig. 5(d)). The increase in number of strokes may further increase the bonding strength that already formed by the resin and hardener.
5. From Fig. 5(e), when the percentage of hardener is increased along with curing time, the compression strength is found to increase. The long curing time allowed the hardener to react more and form strong bonding between the grains.
6. Compression strength has shown a non-linear relationship with increase in number of strokes. Moreover, compression strength is found to increase non-linearly with the increase in curing time (Fig. 5(f)). The reason for this is same as the one explained above.

The compression strength in un-coded form is presented in Eqn. (6).

$$CS_{CCD} = -749.644 + 3724.78*X_1 - 223.345*X_2 + 32.9542*X_3 + 45.3688*X_4 - 979.459*X_1^2 + 3.48177*X_2^2 - 21.0879*X_3^2 - 0.143696*X_4^2 + 10.1535*X_1*X_2 + 57.4681*X_1*X_3 - 0.742067*X_1*X_4 - 2.75121*X_2*X_3 - 0.608172*X_2*X_4 + 1.73871*X_3*X_4 \quad (6)$$

The results of ANOVA test show that all the terms, such as linear, square, interaction and lack of fit terms are found to be significant on compression strength. Moreover, the coefficient of correlation for compression strength is found to be equal to 0.917. From these results it is clear that developed non-linear model for the response – compression strength is statistically adequate and will be used for making predictions.




(f)

Fig. 5: Surface plots of compression strength with: (a) Percentage of resin and hardener (b) percentage of resin and number of strokes (c) percentage of resin and curing time (d) percentage of hardener and number of strokes (e) percentage of hardener and curing time (f) number of strokes and curing time.

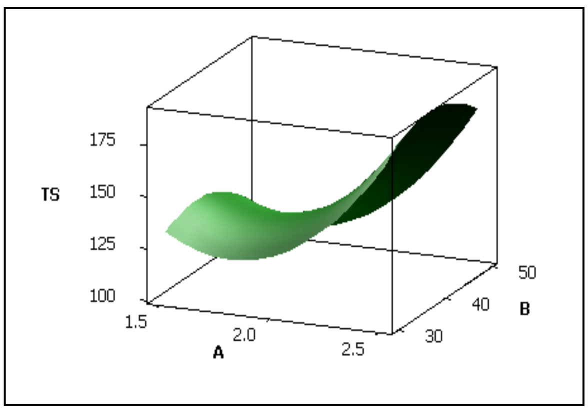
*Response – Tensile Strength*

The non-linear relationship of the tensile strength with input process parameters, namely percentage of resin, of hardener, number of strokes and curing time is given by the Eqn. (7).

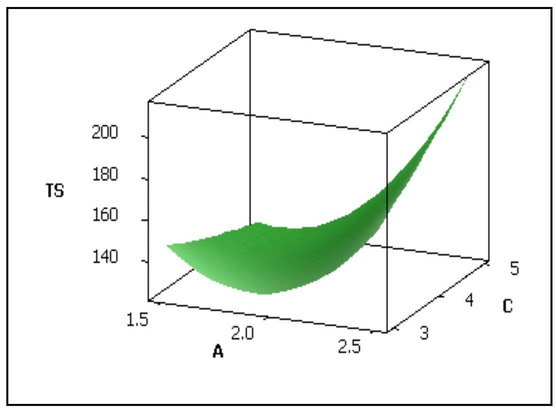
$$TS_{CCD} = 134.917 + 26.305*A - 5.198*B + 5.988*C - 6.846*D + 27.228*A^2 - 13.176*B^2 + 1.568*C^2 - 9.809*D^2 + 4.214*A*B + 15.802*A*C + 16.587*A*D + 5.667*B*C + 2.38*B*D + 7.371*C*D \quad (7)$$

The results of significance test shows that all the factors, square terms and interaction terms are found to be significant on the tensile strength with 95 percent confidence level. Moreover, the following observations are drawn from the surface plots of tensile strength.

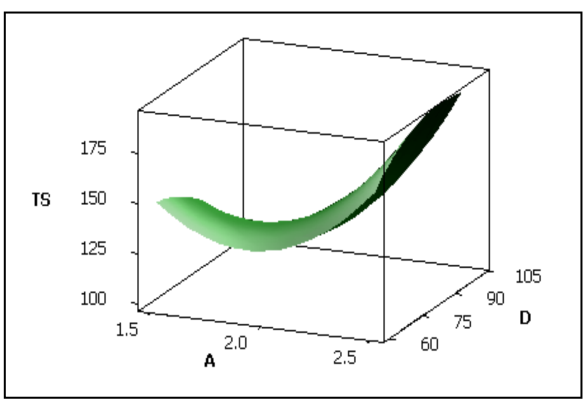
1. Tensile strength is seen to increase with the increase in percentage of resin, whereas tensile strength is found to increase initially with percentage of hardener and then decreases slightly with the further increase in percentage of hardener (Refer to Fig. 6(a)).
2. From Fig. 6(b), the combined increase in percentage of resin and number of strokes increases the tensile strength.
3. The tensile strength is found to increase with the increase in percentage resin and curing time (Fig. 6(c)).
4. The tensile strength is initially seen to increase with the increase in percentage hardener and then decreases with the further increase in percentage of hardener. Moreover, the tensile strength is found to increase linearly with the increase in number of strokes (Refer to Fig. 6(d)).
5. From Fig. 6(e), with increase in both the percentage of hardener and curing time, the tensile strength is seen to increase initially and then started decreasing with the further increase in percentage of hardener and curing time.
6. The tensile strength has shown a linear variation with the increase in number of strokes, whereas tensile strength has shown a parabolic variation with maximum value at the mean value of curing time (Fig. 6(f)).



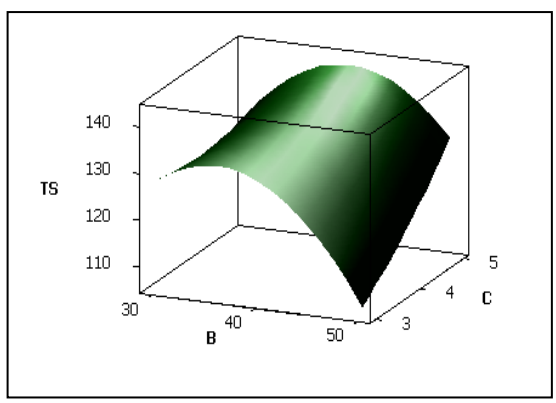

(a)



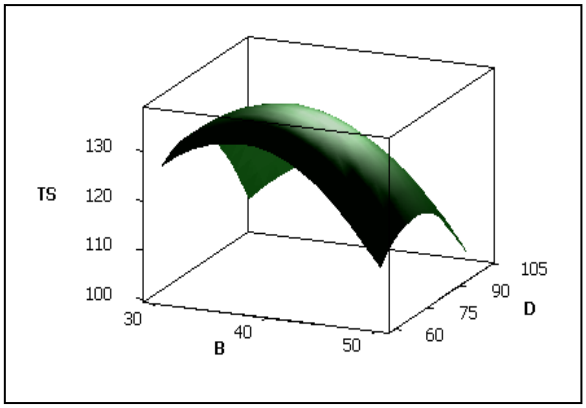

(b)



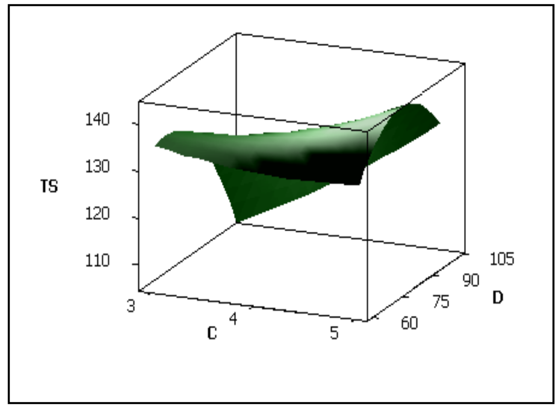

(c)




(d)




(e)




(f)

Fig. 6: Surface plots of tensile strength with: (a) Percentage of resin and hardener (b) percentage of resin and number of strokes (c) percentage of resin and curing time (d) percentage of hardener and number of strokes (e) percentage of hardener and curing time (f) number of strokes and curing time.

The response equation for tensile strength in un-code form is given in Eqn. (8)

$$TS_{CCD} = 979.326 - 675.852*X_1 + 5.11367*X_2 - 121.909*X_3 - 1.68779*X_4 + 108.910*X_1^2 - 0.131762*X_2^2 + 1.56760*X_3^2 - 0.02452*X_4^2 + 0.8428*X_1*X_2 + 31.6031*X_1*X_3 + 1.65868*X_1*X_4 + 0.56667*X_2*X_3 + 0.01193*X_2*X_4 + 0.3685*X_3*X_4 \quad (8)$$

The coefficient of correlation for the response tensile strength is seen to be equal to 0.996. Moreover, the results of ANOVA show that the non-linear relationship of tensile strength is statistically acceptable.

*Response – Shear Strength*

The coded expression that shows the non-linear relationship between shear strength and input process parameters are given in Eqn. (9).

$$SS_{CCD} = 367.266 + 59.518*A - 23.723*B + 18.715*C + 33.873*D + 106.344*A^2 - 53.364*B^2 + 7.611*C^2 - 26.383*D^2 + 41.516*A*B - 1.163*A*C + 38.705*A*D + 7.143*B*C - 19.23*B*D + 7.96*C*D \quad (9)$$

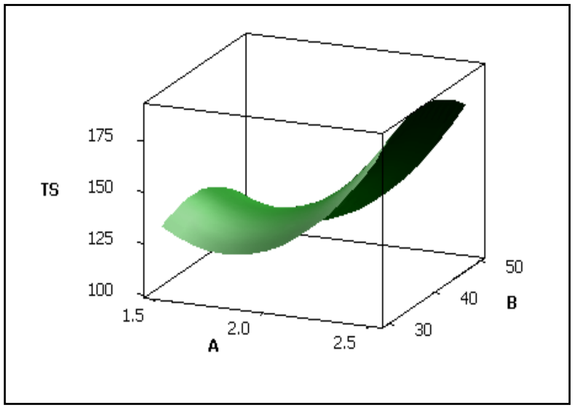
From the results of significance test, it has been observed that all the main terms (A, B, C and D), some of the square terms (except $C^2$, $D^2$) and some of their interaction terms (besides AC, BC and CD) makes significant contribution on shear strength. In addition to this, surface plots are also drawn for the response – shear strength and the following observations are drawn.

1. Shear strength is found to decrease with the increase in percentage of resin and seen to reduce slightly with the increase in percentage of hardener (refer to Fig. 7(a)).
2. From Fig. 7(b), shear strength is seen to increase with increase in percentage of resin and number of strokes.
3. Increase in percentage of resin and curing time would result in increased shear strength (Fig. 7(c)).
4. Shear strength is seen to be decreased with increase in percentage of hardener, whereas increase in the number of strokes result in linearly increasing shear strength (refer to Fig. 7(d)).
5. From Fig. 7(d), with the increase in both the percentage of hardener and curing time, shear strength is found to increase initially and starts decreasing with the further increase in hardener and curing time.
6. Shear strength is seen to increase with increase in the number of strokes and curing time (Fig. 8(d)).

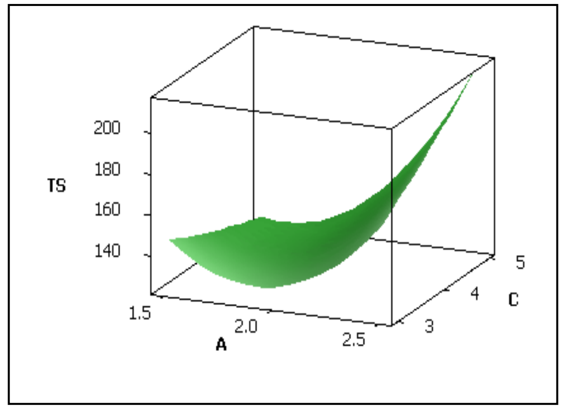
The relationship of shear strength with the input parameters in un-coded form is given by Eqn. (10).

$$SS_{CCD} = 1759.89 - 2214.93*X_1 + 28.548*X_2 - 97.933*X_3 + 6.7608*X_4 + 425.375*X_1^2 - 0.53363*X_2^2 + 7.6108*X_3^2 - 0.06595*X_4^2 + 8.30328*X_1*X_2 - 2.32575*X_1*X_3 + 3.87053*X_1*X_4 + 0.71432*X_2*X_3 - 0.09617*X_2*X_4 + 0.3980*X_3*X_4 \quad (10)$$

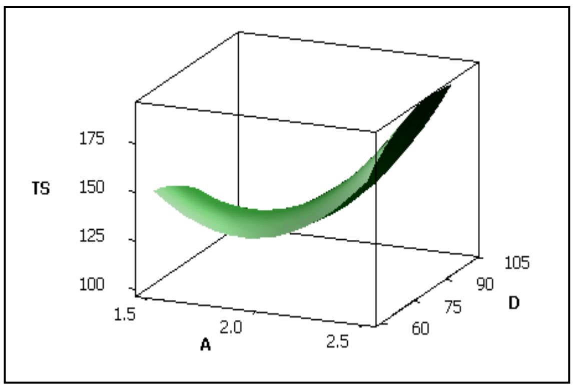
The coefficient of correlation for shear strength is seen to be equal to 0.941. Moreover, the results of the ANOVA test indicate the adequacy of the model. It is important to note that the results of ANOVA and coefficients of correlation for all the responses are quite satisfactory. Thus the developed models will be suitable for predicting the responses for the input parameters set within their limits. It has been observed that, the compression strength of the specimen are found to be maximum followed by shear and tensile strengths.



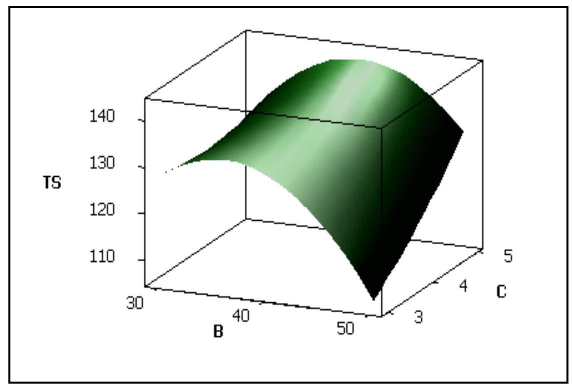

(a)



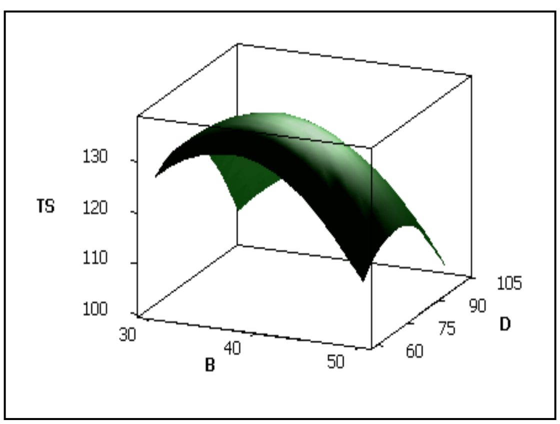

(b)



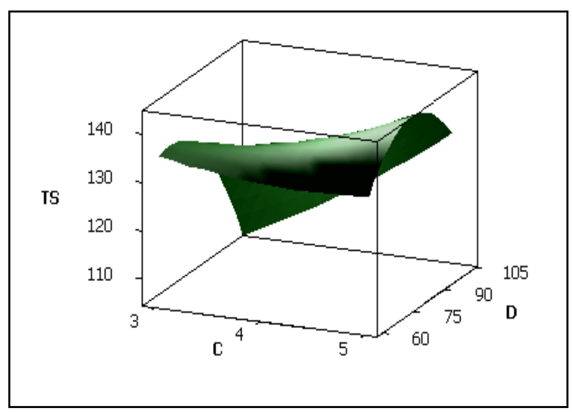

(c)




(d)




(e)



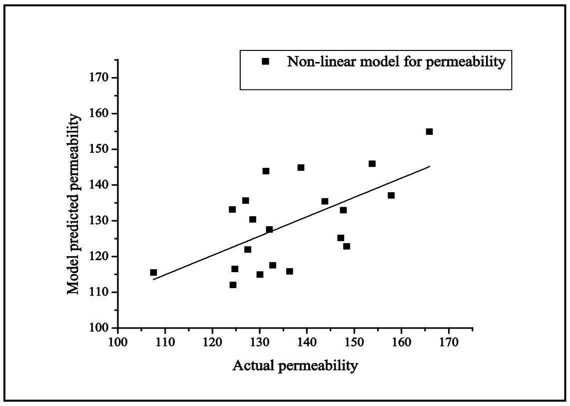

(f)

Fig. 7: Surface plots of shear strength with: (a) Percentage of resin and hardener (b) percentage of resin and number of strokes (c) percentage of resin and curing time (d) percentage of hardener and number of strokes (e) percentage of hardener and curing time (f) number of strokes and curing time.

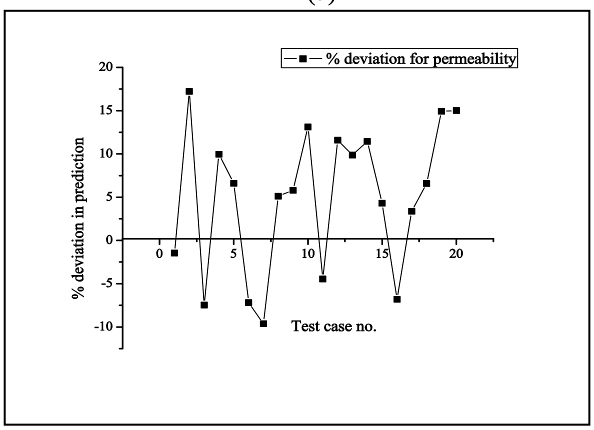
*B Testing of the Models*

The prediction accuracy of the developed models can be determined by conducting conformity tests. In this procedure twenty test cases (refer to Appendix-B) are generated at random by assigning intermediate values to the process variables and for each combination the outputs are determined experimentally. The results are presented and discussed below.

Figure 9(a) shows the comparison of the model predicted permeability values with their respective experimental values. It has been observed that the data points are equally distributed on both sides of the y=x line. This shows that the model is able to make predictions with reasonably good accuracy. The values of percentage deviation in prediction of permeability are shown in Fig. 9(b).



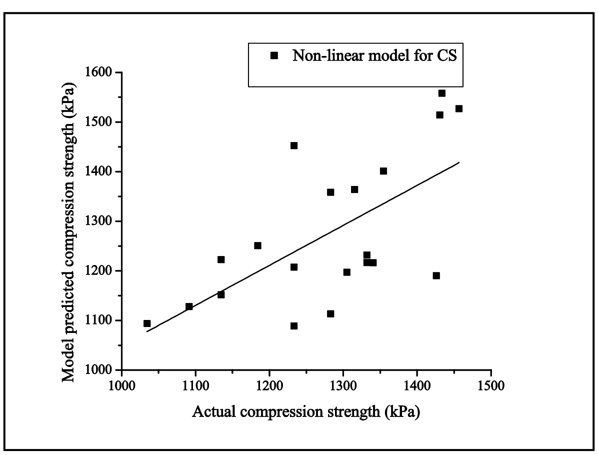

(a)



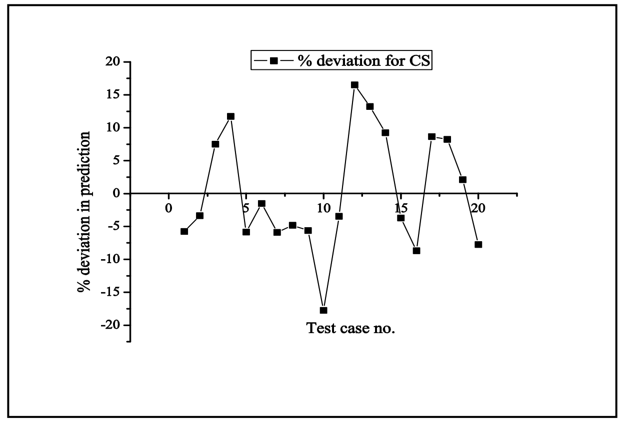

(b)

Fig. 9: Comparison of the model predicted values of permeability with the experimental results for test cases (a) actual permeability vs model predicted permeability (b) Values of percentage deviation in prediction of permeability.

It has been observed that the percentage deviation values for permeability are found to lie on both the positive and negative sides. Moreover, the values are found to vary between -9.615 and +17.218 percent.



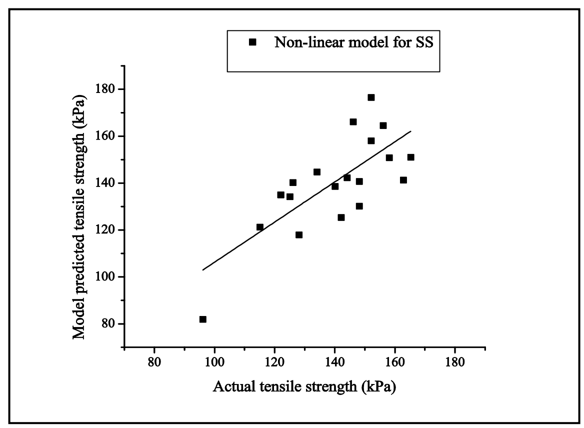

(a)



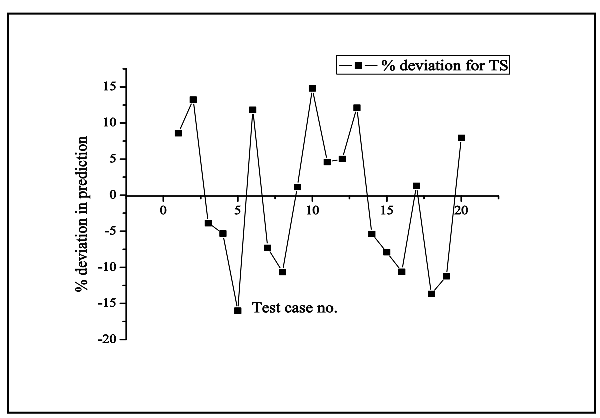

(b)

Fig. 10: Comparison of the model predicted values of compression strength with the experimental results for test cases (a) actual compression strength vs model predicted compression strength (b) values of percentage deviation in prediction of compression strength.

Figs. 10(a) and (b) shows the scatter plot and percentage deviation values for prediction of compressive strength. The percentage deviation values for the non-linear model of the response – compression strength is seen to lie in between -17.749 and +16.5164. Fig. 11(a) compares the actual and predicted values of the response – tensile strength by the non-linear regression model.



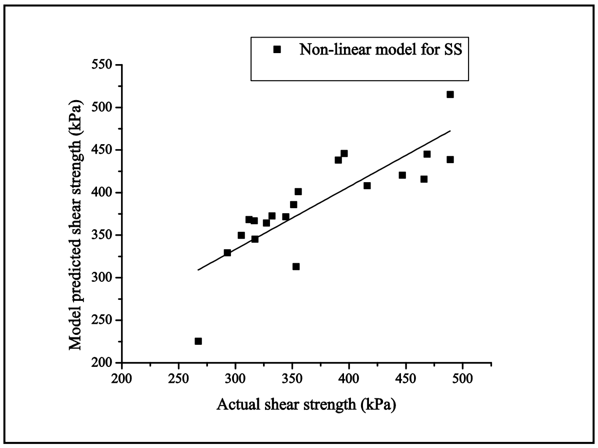

(a)



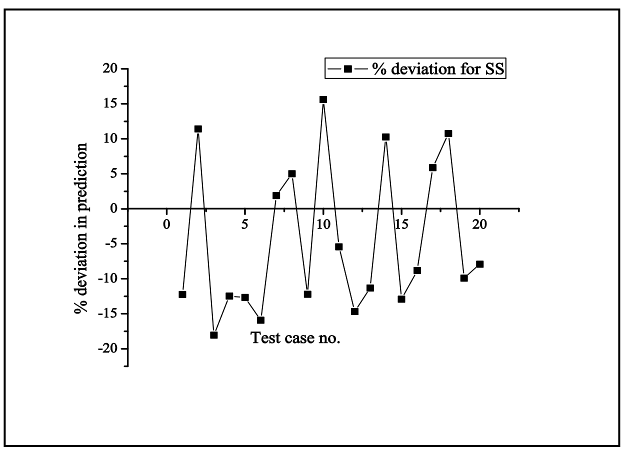

(b)

Fig. 11: Comparison of the model predicted values of tensile strength with the experimental results for test cases (a) actual tensile strength vs model predicted tensile strength (b) values of percentage deviation in prediction of tensile strength.

The performance of the non-linear model is seen to be better as the data points are close to the ideal line. The values of percentage deviation in prediction of tensile strength are shown in Fig. 11(b). It is interesting to note that percentage deviation values are found to lie in the range of -15.999 to +14.791.




(a)




(b)

Fig. 12: Comparison of the model predicted values of shear strength with the experimental results for test cases (a) actual shear strength vs model predicted shear strength (b) values of percentage deviation in prediction of shear strength.

Figs. 12(a) and (b) shows the scatter plot and percentage deviation plots for making the comparison of experimental shear strength with the model predicted shear strength. It is important to note that the percentage deviation values ranged from -18.059 to 15.627 percent.

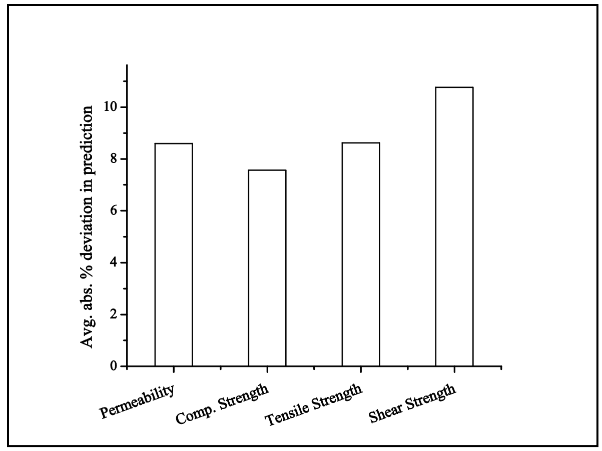



Fig. 13: Bar chart showing the average absolute percentage deviation in prediction of all the responses.

The variation of average of absolute percentage error of all the responses is shown in Fig. 13. It can be observed that the average of absolute percentage deviation for various responses, such as permeability, compression strength, tensile strength and shear strength are seen to be equal to 8.594, 7.568, 8.623 and 10.764, respectively. From these results it can be concluded that the non-linear model has given reasonably good predictions for all the responses.

## IV. CONCLUSION

Non-linear regression models are developed for the responses - permeability, compression strength, tensile strength and shear strength of a chromite-based resin bonded sand core system. Four controllable factors chosen for the experiments are percentage of resin, of hardener, number of strokes and curing time. Central composite design of experiments is used to develop the non-linear model with the parameters set at three levels. Once the models are developed, their statistical adequacy has been tested ANOVA test and coefficient of correlation values. It is to be noted that all the models developed are found to be statistically adequate. To validate the developed models, twenty test cases are examined and the deviations in predictions are determined. The results of this validation show that non-linear models developed for chromite-based resin bonded sand core system has given better predictions for all the responses. The methodology and the regression models can be used in the foundries to know the response values for different combination of input parameters, without conducting experiments. This will assist the foundrymen to set the process parameters, depending on their requirements.

## REFERENCES


[1] Steel Casting Hand Book, Sixth Edition, Edited by Malcom Blair and Thomas L. Stevens, ASM International, First Edition, 1985.

[2] D. Sitaramaiah, R.L. Kumar and A.K. Kar, Some experiments on cold setting organic binders, The British Foundryman, Vol. 63, pp. 30-34, 1970.

[3] B.J. Shetty, M.K. Muralidhara and P.F. Sanaulla, Studies on properties of self setting sand using molasses as a binder and calcium oxide as a hardener, Indian Foundry Journal, Vol. XXXIX, No. 7, pp. 3-8, 1971.

[4] D.M. Trinowski, New Cold box Binder System for improved Productivity, AFS Transactions, Vol. 107, pp. 51-57, 1999.

[5] G. Ding, Q. Zhang and Y. Zhou, Strengthening of cold-setting resin sand by the additive method, Journal of Material Processing Technology, Vol. 72, pp. 239-242, 1997.

[6] J.D. Howden, Chromite double skin defect on heavy section steel castings, 4th Asian Foundry Congress, pp. 51-64, October 1996.

[7] W. Liu, Y. Li, X. Qu and X. Liu, Study on binder system of CO2 cured phenol formaldehyde resin used in foundry, 68th World Foundry Congress, pp. 313-317, Feb. 2008.

[8] Y. Zhang, Y. Xue, J. Huang, S. Li, L. Xia and C. Huang, Mechanism of strength loss of no-bake phosphate bonded sand mold/core, Journal of Wuhan University of Technology-Material Science Edition, Vol. 24, No. 1, pp. 5-8, 2009.

[9] I. Caylak and R. Mahnken, Thermo-mechanical characterization of a cold-box sand including optical measurements, International Journal of cast Metals Research, Vol. 23, No. 3, pp. 176-184, June 2010.

[10] Douglas M. Trinowski, Foundry, Phenolic Resins: A Century Progress, Vol. 3, pp. 451-502, 2010.

[11] S.I. Bakhtiyarov and R.A. Overfelt, CFD modeling and experimental study of resin bonded sand/air two-phase flow in sand core making process, Powder Technology, Vol. 133, No. 1-3, pp. 68-78, 2003.

[12] G. Wen-bang, C Li-liang, L. Rui-xiang and H. Jing, Derivation and application of time step model in solidification process simulation, China Foundry, Vol. 4, No. 3, pp. 206-209, 2007.

[13] S.K. Shaha and M.M. Haque, Simulation of heat flow in computational method and its verification on the structure and property of grey cast iron, American Journal of Applied Sciences, Vol. 6, No.6, pp. 795-799, 2010.

[14] Douglas C. Montgomery, Design and Analysis of Experiments, Fifth Edition, John Wiley & Sons, Inc, 2001.

[15] B.K. Dhindaw, M. Chakraborty, Study and control of properties and behavior of different sand systems by application of statistical design of experiments, Proc. Of 41st International Foundry Congress, Belgique, pp. 9-14, 1974.

[16] S. Kumar, A.K. Gupta and P. Chandna, Optimization of process parameters of pressure die casting using taguchi methodology, World Academy of Science, Engineering and Technology, Vol. 68, pp. 709-713, 2012.

[17] R.A. Upadhye and I.P. Keswani, Optimization of sand casting process parameters using taguchi method in foundry, International Journal of Engineering Research & Technology, Vol. 1, No. 7, pp. 1-9, 2012.

[18] A. Mandal and P. Roy, Modeling the compressive strength of molasses cement sand system using design of experiments and back propagation neural networks, Journal of Material Processing Technology, Vol. 180, No. 1-3, pp. 167-173, 2006.

[19] M. B. Parappagoudar, D.K. Pratihar and G.L. Datta, Linear and non-linear statistical modeling of green sand mould system, International Journal of Cast Metal Research, Vol. 20, No.1, pp. 1-13, 2007.

[20] [18] M.B. Parappagoudar, D.K. Pratihar and G.L. Datta, Linear and non-linear modeling of cement bonded moulding sand system using conventional regression analysis, Journal of Materials Engineering and Performance, Vol. 17, No.4, pp. 472-481, 2008.

[21] R.R. Kundu and B.N. Lahiri, Study and statistical modeling of green sand mould properties using RSM, International Journal of Materials and Product Technology, Vol. 31, pp. 143-158, 2008.

[22] J. Bast, W. Simon and E. Abdullah, Investigation of cogs defects reason in green sand mould, Archives of Metallurgy and Materials, Vol. 55, No.3, pp. 749-755, 2010.

[23] B. Surekha, B.P. Kishore, A.A. Kumar, B.N. Mahesh, B.U. Lakshmi and V.R.K. Rao, Linear modeling of quartz-based resin bonded sand mould system using design of Experiments, CIIT International Journal of Data Mining and Knowledge Engineering, Vol. 3, No. 11, pp. 697-704, 2011.

[24] A.R. Krishnamoorty, Sand Practices, The Institute of Indian Foundrymen, Calcutta, 1996.



**B. Surekha** working as Assistant Professor in Mechanical Engineering Department, Gandhi Engineering College, Bhubaneswar- 752054, Odissa, India. She did her B.Tech in Mechanical Engineering at JNT University, Hyderabad, India in 2000, and completed her M.Tech (Compueter Integrated Manufacturing) from NIT Warangal, India in 2003. She is working at present as external research scholar in the Department of Mechanical Engineering of JNT University, Hyderabad, India. She has published around 20 technical papers. Her areas of interests include foundry engineering, advanced manufacturing systems and soft computing.

**D. Hanumantha Rao** did his B. Tech in Mechanical engineering from Gulbarga University, Karnataka, India in 1986 and M.Tech in Machine Design from JNTU Kakinada, India in 2000. He received his Ph. D in Mechanical Engineering from JNTU Hyderabad, India in 2006. Presently he is working as the Principal and Professor of Mechanical engineering at Matrusri Engineering College, Hyderabad, India. He has published around 40 publications in various International and National Journals and Conferences. His research interests include foundry, casting and simulation of manufacturing processes using ANSYS.

**G. Krishna Mohana Rao** is a member of ASME, ISTE, IE(I). He was born at Machilipatnam, AP, India on 05.05.1970. He received his bachelors' degree in mechanical engineering from Nagarjuna University, AP, India in the year 1992.Later, he was awarded masters degree in mechanical engineering by the Indian Institute if Science, Bangalore, India in the year 1994. He received his doctoral degree in mechanical engineering from JNT University, Hyderabad, AP, India in the year 2007. He has been working for JNT University, AP, India since 1994. He is on the review board for many international journals. He has published 40 technical papers in international journals and conferences. He co-authored a book on engineering mechanics published by Pearson education. He visited countries including USA, UK, Egypt, UAE, China, Malaysia, Singapore, Hongkong, Thailand, Italy, Switzerland, Austria and Greece for delivering plenary lectures, chairing technical sessions and to present his papers in various international conferences. His areas of research include non-traditional machining, casting, welding. Presently, he is guiding 16 research students in the area of mechanical engineering.

**Pandu R Vundavilli** received his B.Tech. in Mechanical Engineering from Jawaharlal Nehru Technological University, Kakinada-533003, India and M.Tech. in Computer Integrated Manufacturing from National Institute of Technology,Warangal-506004, India in 2000 and 2003, respectively. From 2003 to 2005, he worked as a faculty member at the Koneru Lakshmaiah College of Engineering, Vaddeswaram-522502, India. He received hid Ph.D. in Mechanical Engineering from Indian Institute of Technology, Kharagpur-721302, India in 2009. He is working at present as Asst. Professor in the School of Mechanical Sciences of IIT Bhubaneswar - 751013, India. His research interests include modeling and simulation of manufacturing systems, robotics and soft computing. He has published around 50 publications in various International and National Journals and Conferences.

**M.B. Parappagoudar** did his engineering graduation in Industrial & Production Engineering from B.V. B. college of Engineering & Technology, Hubli, affiliated to Karnataka University, Dharwad. He obtained his Master of Engineering degree in Production Management from Gogte Institute of Technology, affiliated to Karnataka University, Dharwad, India, in 1996. He joined Indian Institute of Technology, Kharagpur in 2004, as a Research Scholar, in the Mechanical Engineering Department under the Quality Improvement Program funded by the MHRD, Govt. of India. Further, he obtained Ph.D. degree in Mechanical Engineering from Indian Institute of Technology, Kharagpur-721302, India during 2008. Presently he is working as the Principal and Professor of Mechanical engineering at Chhatrapati Shivaji Institute of Technology, Durg India. He has published around 30 research papers in reputed International Journals and Conferences. His research interests include application of statistical and soft computing tools in manufacturing engineering.

## APPENDIX-A: Design matrix for central composite design

| S.No | Input parameters | | | | Responses | | | |
|---|---|---|---|---|---|---|---|---|
| | A | B | C | D | Compression strength (kPa) | Tensile strength (kPa) | Shear strength (kPa) | Permeability |
| 1 | -1 | -1 | -1 | -1 | - | - | - | - |
| 2 | +1 | -1 | -1 | -1 | - | - | - | - |
| 3 | -1 | +1 | -1 | -1 | - | - | - | - |
| 4 | +1 | +1 | -1 | -1 | - | - | - | - |
| 5 | -1 | -1 | +1 | -1 | - | - | - | - |
| 6 | +1 | -1 | +1 | -1 | - | - | - | - |
| 7 | -1 | +1 | +1 | -1 | - | - | - | - |
| 8 | +1 | +1 | +1 | -1 | - | - | - | - |
| 9 | -1 | -1 | -1 | +1 | - | - | - | - |
| 10 | +1 | -1 | -1 | +1 | - | - | - | - |
| 11 | -1 | +1 | -1 | +1 | - | - | - | - |
| 12 | +1 | +1 | -1 | +1 | - | - | - | - |
| 13 | -1 | -1 | +1 | +1 | - | - | - | - |
| 14 | +1 | -1 | +1 | +1 | - | - | - | - |
| 15 | -1 | +1 | +1 | +1 | - | - | - | - |
| 16 | +1 | +1 | +1 | +1 | - | - | - | - |
| 17 | 0 | 0 | 0 | 0 | - | - | - | - |
| 18 | -1 | 0 | 0 | 0 | - | - | - | - |
| 19 | +1 | 0 | 0 | 0 | - | - | - | - |
| 20 | 0 | -1 | 0 | 0 | - | - | - | - |
| 21 | 0 | +1 | 0 | 0 | - | - | - | - |
| 22 | 0 | 0 | 0 | 0 | - | - | - | - |
| 23 | 0 | 0 | -1 | 0 | - | - | - | - |
| 24 | 0 | 0 | +1 | 0 | - | - | - | - |
| 25 | 0 | 0 | 0 | -1 | - | - | - | - |
| 26 | 0 | 0 | 0 | +1 | - | - | - | - |
| 27 | 0 | 0 | 0 | 0 | - | - | - | - |

**APPENDIX-B: Input-Output data of the test cases**

| Test No | % Resin (A) | % Hardener (B) | Number of strokes (C) | Curing time (D) | Avg. compression strength (CS) in kPa | Avg. tensile strength (TS) in kPa | Avg. shear strength (SS) in kPa | Avg. permeability number (P) |
|---|---|---|---|---|---|---|---|---|
| 1 | 2.4 | 32.5 | 3 | 65 | 1034.32 | 165.25 | 332.08 | 128.56 |
| 2 | 1.6 | 46 | 3 | 63 | 1091.42 | 162.84 | 353.37 | 148.49 |
| 3 | 2.3 | 32 | 5 | 68 | 1332.12 | 152.18 | 311.99 | 107.56 |
| 4 | 1.7 | 45.5 | 5 | 62 | 1233.45 | 115.14 | 292.81 | 147.68 |
| 5 | 2.45 | 47.5 | 5 | 63 | 1430.8 | 152.52 | 395.73 | 165.92 |
| 6 | 1.75 | 33.5 | 3 | 87 | 1134.77 | 142.17 | 316.58 | 124.23 |
| 7 | 2.25 | 31.6 | 3 | 90 | 1282.78 | 125.08 | 415.93 | 131.29 |
| 8 | 2.38 | 48 | 3 | 94 | 1456.79 | 122.06 | 468.71 | 153.80 |
| 9 | 2.28 | 34.8 | 3 | 92 | 1184.11 | 140.92 | 390.52 | 143.79 |
| 10 | 1.78 | 49.5 | 3 | 98 | 1233.45 | 96.43 | 267.23 | 157.83 |
| 11 | 2.48 | 47 | 3 | 96 | 1354.26 | 158.10 | 488.96 | 138.71 |
| 12 | 2.1 | 36 | 4 | 70 | 1425.87 | 148.13 | 305.11 | 130.04 |
| 13 | 1.8 | 38.5 | 4 | 79 | 1282.78 | 148.47 | 327.23 | 124.38 |
| 14 | 2.35 | 39 | 4 | 74 | 1340.48 | 156.19 | 488.96 | 132.75 |
| 15 | 2.2 | 33 | 4 | 85 | 1315.43 | 134.39 | 355.20 | 127.49 |
| 16 | 2.15 | 46.8 | 4 | 72 | 1433.45 | 122.08 | 317.23 | 127.03 |
| 17 | 2.25 | 37 | 3 | 84 | 1332.12 | 144.42 | 446.75 | 132.04 |
| 18 | 2.28 | 39.5 | 5 | 69 | 1304.80 | 146.17 | 465.84 | 124.76 |
| 19 | 2.18 | 36.5 | 3 | 78 | 1233.45 | 126.26 | 351.17 | 147.18 |
| 20 | 1.9 | 38 | 4 | 95 | 1134.77 | 128.64 | 344.28 | 136.33 |