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Experimental Investigation of the Influence of Sand and Binder Composition on the Mold Properties of Alkyd Type No-Bake Chemically Bonded Sand-Casting System

J. Keerthana
UG Student, PSG College of Technology, Coimbatore, Tamil Nadu, India
E-mail: jayakumarkeerthana8@gmail.com

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Abstract - **In comparison to green sand moulds, chemically bonded resin sand moulds have better dimensional accuracy, surface quality, and sand mould qualities. To survive sand drops when pouring molten metal, the mould cavity formed using a chemically bonded sand mould technique must have appropriate permeability, strength, and hardness. The desire for better permeability, strength, and mould hardness is based on a thorough investigation and analysis of the affecting parameters, such as resin percentage, hardener, and catalyst. The influence of binder content on the moulding qualities of silica sand bound with Alkyd oil urethane binder was investigated. Using a sieve shaker, the experimental materials were sieved and manually blended with the binders. AFS standard test specimens (50 mm diameter by 50 mm height) were prepared using a sand rammer, and four key moulding parameters were determined using a universal sand strength machine, permeability meter, and mould hardness tester: green compression strength (GCS), green shear strength (GSS), permeability, and mould hardness. For the minimal experiments, Box-Behnken experimental matrices were used, and the statistical significance of influencing factors and their interactions will be identified to manage the process. To statistically validate the model, an analysis of variance (ANOVA) test was performed using Minitab. Mold hardness, strength, and permeability will each have their own mathematical equation, which was stated as a nonlinear function of input factors based on experimental input-output data. To optimize the process parameters, a response optimizer (using Minitab) has been used. The results revealed that increasing the resin concentration from 1% to 2% enhances permeability and GSS while decreasing GCS and mould hardness. Hardener was increased from 18 to 20%, which resulted in a drop in permeability and GSS but an increase in GCS and mould hardness. Similarly, increasing the catalyst concentration from 2% to 10% reduces permeability and mould hardness while increasing GCS and GSS.**

Keywords: **Sand, Binder, Mold Properties, Alkyd Type, Sand-Casting System**

I. INTRODUCTION

Casting is the most fundamental manufacturing method for producing metal engineering objects [1]. It contributes significantly to the development of modern equipment for power, communication, transportation, agro-allied, construction, space, agricultural, chemical, and petrochemical industries, and other sectors. Products of almost any form and size may be manufactured at low prices with dimensional accuracy and reduced scrap [2]. Sand casting, shell molding, injection molding, and other forms of castings exist. Sand casting is the most common type of casting in the world because of its cost-effectiveness, versatility, and wide range of alloys. Sand casting is separated into green sand molding, chemicals and molding, dry sand molding, no-bake sand molding, and cold box molding based on the kind of sand and binding agents employed [1]. Among these, greensand molding is a versatile, quick, and inexpensive method of creating molds for high-quality ferrous and non-ferrous castings. Greensand is made out of silica sand, water, bentonite, and additional ingredients including coal dust for iron uses. But it is complex since it necessitates hot pattern plates and curing ovens; as a result, it is mostly utilized for tiny castings [3].

Molding sand for metal casting is often made from natural deposits or a manufactured mixture of a refractory base sand grain, binder, and moisture that creates the ideal bonding environment. The qualities of the molding sand are determined by each element. The level of control over the critical aspects of molding sand is limited and constrained when using natural sand [4]. The modern foundry uses a chemical bonded no-bake sand mold system as it has enhanced shelf life, strength, dimension accuracy, and surface finish [5]. Sand molds were preferred to permanent molds due to several technical advantages, namely, low process cost, ease of mold making, minimized constraints on part geometry, and castability of different metals [6]. Sand drop defects in casting are always the result of mold hardness, which in turn is influenced by grain fineness, the quantity of binder (resin, catalyst, and hardener), curing time, degree of ramming, and so on [7].

In synthetic sand, there are three major constituents (resin, hardener, and catalyst) that are properly selected to produce desired attributes within acceptable limitations. As a result, the impact of these key ingredients on the qualities of molding sand must be examined in order to determine the best compositional blend [4]. Deshpande Anand *et al.*, [1] studied the mold hardness of a molding sand specimen using the Taguchi technique using an L9 orthogonal array and experiments were conducted randomly. The factors include the amount of resin, amount of hardener, and setting time were considered. It was observed that the amount of resin and set time are significant for mold hardness. Dr. G. Laxmaiah *et al.,* [9] attempted to optimize the clay, water, and additive (tamarind kernel powder) contents in the green sand. It was found that clay has the maximum contribution in GCS, GSS, and permeability and water have the maximum contribution in DCS and DSS. Shailee G. Acharya *et al.,* [10] investigated the effect of sand temperature, amount of resin, and amount of catalyst on compressive strength and scratch hardness of the furan sand mold. It was found that sand temperature was the dominant contributor to both responses such as compressive strength and scratch hardness and the next contributor was an amount of resin followed by an amount of catalyst or hardener. Dhruval Patel *et al.,* [13] studied the mold properties such as compression strength, permeability, hardness, and shear strength and comparisons have been made with different binders. The process parameters such as silica grains, moisture, and clay % were optimized using Taguchi L9 orthogonal array.

A no-bake binder creates mechanical strength without requiring a baking cycle. Fast hardening, strength, collapsibility framing, high strength, high dimensional accuracy, fast hardening rate, high production efficiency, and low labor intensity are also advantages, as well as a plentiful supply of raw materials and a simple manufacturing process to improve the quality of the metal produced [8]. One of the types of no-bake binder systems is the Alkyd No-bake system. The three parts of this system (catalyst) are Part A (resin), Part B (hardener), and Part C (filter) [9]. Most industries add resin, catalyst, and hardener to sand by trial and error, so moulds break at the start of the shift, and employees progressively raise the hardener and resin percentage. However, using too much hardener and resin will make shakeout difficult, and the gases released after pouring the molten metal would be confined due to the reduced permeability [1].

Although the sand-casting technique is advantageous, the traditional method of creating sand molds is time intensive and has a poor output rate. Furthermore, due to the numerous inherent porosities that are likely to promote casting defects, the traditional method of sand casting produces poor mechanical and surface properties [11]. It's worth noting that the mold quality is mostly responsible for the casted product's quality. As a result, improving the mold's quality is critical if we want to make precise items the first time. Squeeze pressure on the sand mold after it has been developed might be used to solve sand casting problems. Based on these findings, it was understood that not much work was done on Alkyd No-bake type sand mold systems, and also the property of mold is highly influenced by the process variables. Proper control of process parameters is essential to get good quality castings i.e., castings with less sand drop defect. In the present study, the effect of resin, hardener, and catalyst % on the mold hardness, permeability, green compression, and shear strength (GCS & GSS) has been investigated. The aim is to find the optimum process parameters value of the Alkyd type no-bake sand casting for the desired mold properties.

II. MATERIALS AND METHODS

A. Materials

This research work focuses on alkyd oil urethane no-bake binder with the goal of studying and understanding the effect of the binder composition, including the content and ratio of the three parts (alkyd resin, catalyst, and hardener) on mold properties with silica sand. The base sand size is maintained constant throughout the experimental runs whose average fineness number was in the range of 45-50. The composition of silica sand is presented in table I. A standard sieve shaker is used to check the sand fineness number.

TABLE I CHEMICAL COMPOSITION OF SILICA SAND

Compound	**Al203**	**SiO2**	**Fe2O3**	**Cr2O3**	**TiO2**	**K2O**	**CaO**	**MgO**	**MnO2**	**Na2O**
Conc %	1.10	97.25	0.15	0.01	0.15	0.18	0.06	0.10	0.01	0.14

Part A is alkyd oil urethane resin. Part B is a liquid amine or metallic catalyst, also called an alkyd activator. Part C is a polymeric MDI (methyl di-isocyanate), which is a cross linking agent. The resin and catalyst control the degree and the time of binding, respectively. The alkyd resin provides a long work time and still achieves maximum hardness when completely cured. Major advantages are high strength, moderate rate of gas evolution, good humidity resistance, and fair erosion resistance. It is found to be equally suitable for producing small, medium, or large molds. The preparation of sand for the Alkyd type no-bake system is represented in table II.

TABLE II SAND PREPARATION SYSTEM FOR ALKYD TYPE NO BAKE SYSTEM

Sl. No.	**Content**	**Resin (By weight of sand)**	**Hardener (By weight of resin)**	**Catalyst (By weight of resin)**
1	Alkyd No-bake System	1-2%. (Alkyd oil type resin)	18 to 20% (Isocyanate)	2 to 10% of resin by Wt. (Amine)

The equipment used included a sieve shaker, standard sand rammer, universal sand strength machine, permeability meter, and mold hardness tester for testing the mold properties.

B. Selection of Process Parameters and Level Values

The input parameters considered in this study include a percentage of resin, hardener, and catalyst. The study's response factors include mold hardness, permeability, green compression, and shear strength. The pictorial representation of input and output parameters is shown in figure 1. The level values of the input parameters chosen for the experimental study are shown in table III.

Fig. 1 Input-output model for Alkyd type no-bake sand casting process

TABLE III SELECTION OF LEVEL VALUES FOR ALKYD TYPE NO-BAKE SYSTEM

Alkyd Type	Low	Medium	High
Resin %	1	1.5	2
Hardener %	18	19	20
Catalyst %	2	6	10

C. Construction of Box-Behnken Design

Statistical design of experiments (DOE) is an effective tool to conduct minimum experiments by varying input factors between their respective levels, analysing the factor significance quantitatively, deriving a mathematical expression, and validating model adequacy based on the collected input-output data. The main objective of experimental design is to study the relations between the response as a dependent variable and the various parameter levels. It provides an opportunity to study not only the individual effects of each factor but also their interactions [21].

The primary, square, and interaction effects of the factors on the specified response qualities are estimated using RSM, a statistical experimental design approach. Above all, RSM's generated models have a high accuracy of prediction. For simulating the reactions in the past, researchers employed the Taguchi experimental design approach. However, the prediction results of those models (developed using the Taguchi approach) are less accurate because this approach ignores the effects of interactions and quadratic terms, whereas the prediction results of the Response surface methodology (RSM) are more accurate because this approach takes into account the effects of interactions and quadratic terms [22]. Another consideration that limits the use of the Taguchi design is that it can develop only linear models of responses, which is not the case in most practical applications. On the other hand, RSM offers the flexibility of developing both quadratic and linear models. Thus, more rigorous models are obtained with the use of the RSM approach [23]. Given the supremacy of the RSM approach, it was employed for the present research. Box-Behnken (BB) design is a class of response surface methodology chosen for process optimization. The Box-Behnken design avoids all the corner points and the star points which are extreme points in terms of the region in which we are doing our experiment. They are used to generate higher-order response surfaces using fewer required runs than a normal factorial technique.

The BB design with three factors which has three center points and a total of 15 observations constructed using Minitab software as shown in table IV has been chosen for the experimental study.

TABLE IV BOX-BEHNKEN DESIGN

Exp. No.	Resin %	Hardener %	Catalyst %
1	1	18	6
2	2	18	6
3	1	20	6
4	2	20	6
5	1	19	2
6	2	19	2
7	1	19	10
8	2	19	10
9	1.5	18	2
10	1.5	20	2
11	1.5	18	10
12	1.5	20	10
13	1.5	19	6
14	1.5	19	2
15	1.5	19	10

D. Sieve Analysis

Sieve analysis is a process of grading sand samples into different grain sizes using a stack of standard test sieves and a sieve shaker. The stack of sieves was arranged according to the sieve aperture with the largest aperture on top of the stack and the smallest at the bottom. 100 g of sand was weighed and poured onto the topmost sieve stack. The stack was placed on a sieve shaker and then coupled for effective vibration. The time was set to allow vibrations for a period of 10 seconds. After vibrating for a period of 10 seconds, the sieve shaker stopped automatically. The sieves were dismantled one after the other, beginning with the one on top. The quantity of sand remaining on each sieve was used to determine the grain fineness number. Figure 2 a) & b) shows the sieve shaker equipment and the arrangement of sieves. From the sieve analysis, the average grain fineness number of silica sand passing through the sieves such as 850, 600, 425, 300, 212, 150, 106, 75, and 53 µm is in the range of 45-60 GFN as shown in table 5and it is suitable for both medium and heavy metal casting.

TABLE V SIEVE ANALYSIS AND AFS GRAIN FINENESS NUMBER (GFN) OF SILICA SAND

Sieve No. (μm)	Sand Retained	% of Sand (R)	Multiplier (M)	R×M
850	2.45	2.45	5	24.5
600	1.3	1.3	10	15.6
425	1.05	1.05	15	16.8
300	2.5	2.5	20	55
212	9.5	9.5	30	285
150	13.5	13.5	44	594
106	40.5	40.5	60	2430
75	25	25	75	1875
53	4.5	4.5	85	382.5
pan	1.5	1.5	100	150
Total		99.58		5848.06

$$N = \frac{Total\ product\ (R \times M)}{Total\ \%\ of\ sand\ retained} = \frac{5848.06}{99.58} = 58.72$$

Fig 2 a) Sieve shaker, b) Arrangement of sieves

E. Mould Preparation

The AFS standard cylindrical specimen of Ø 50.8 * 50.8 mm size will be made by hand mixing silica sand with resin, hardener, and catalyst of 130g weight as per the calculations. After the hand mixing of all the ingredients, the prepared mixture will be compacted in the specimen tube by inserting the tube under the plunger and rammed with three drops of the sliding weight by turning the cam handle three revolutions as shown in figure 3a. The specimens for strength tests will be stripped from the tube by inverting over the stripping post and pushing the tube gently downward. While the specimens for the permeability test will be tested while in the tube. The samples fabricated by sand rammers are shown in figure 3b. Then the samples were tested for the mold properties such as mold hardness, permeability, green compression, and shear strength.

Fig. 3 a) Sand rammer equipment b) Fabrication of 15 standard samples

III. RESULTS AND DISCUSSION

A. Experimental Study of Moulding Sand Properties

1. Green Compression Strength (GCS) Test

The GCS test was carried out using the universal sand strength machine (USSM). A freshly prepared AFS standard 50.8 mm diameter by 50.8 mm height test specimen will be inserted in the compression heads. The “START” button was pressed and the magnetic rider gradually moved along the reading scale. When the specimen collapses at its maximum strength, the machine reverses and returns to zero automatically, while the magnetic rider remains in the position of the ultimate strength. The reading shown on the lower edge of the magnetic rider will be recorded by reading the scale designated “Green compression strength” as shown in figure 4a. The failed specimen is then removed from the compression heads as shown in figure 4b.

Fig. 4 a) Universal sand strength machine in compression mode, b) Compression tested specimen

2. Green Shear Strength (GSS) Test

The same USSM was used for the GSS, but this time, the compression heads in the lower position of the machine are replaced with the shear test heads. The shear strength will be recorded when the specimen shears by reading the lower edge of the magnetic rider on the scale designated “Green Shear Strength” as shown in figure 5a and the shear tested specimen was shown in figure 5b.

Fig. 5 a) Universal sand strength machine in shear mode, b) Shear tested specimen

3. Permeability Test

The permeability test was carried out on the AFS standard specimen of 50.8 mm diameter x 50.8 mm height using the permeability meter as shown in figure 6. The permeability meter employs the orifice method for the rapid determination of sand permeability. The specimen, while still in the specimen tube, is mounted on the small orifice of the perm meter and air at constant pressure was applied and the drop in pressure will be measured on a pressure dial-gauge, which will be calibrated directly in permeability numbers.

The permeability number P can be found mathematically, by the formula given below.

$$P = \frac{v.h}{p.a.t}$$

Where

P = permeability number to be determine
v = volume of air passing through the specimen in cm^3
h = height of the specimen in cm (5.08 cm)
p = pressure of air in gm/cm2 (10 gm/cm^2)

a = cross-sectional area of specimen in cm^2 (A standard value of 20.26 cm^2 is generally adopted).

t = time for air to pass in minutes.

$$P = \frac{200 \times 5.08 \times 60}{10 \times 20.26 \times t} = \frac{3007.2}{Time\ in\ seconds}$$

Fig. 6 Permeability Meter

4. Mould Hardness Test

The mould hardness test will be carried out on the AFS standard specimen of 50.8 mm diameter x 50.8 mm height using the core hardness tester as shown in figure 7, which is based on the same principle as the Brinell hardness tester. A steel ball of 50 mm diameter weighing 237 gm is pressed on the mould surface. The depth of penetration of the steel ball will give the hardness of the mould surface on the direct reading dial.

Fig. 7 a) Hardness tester, b) Measuring mould hardness

TABLE VI RESULTS OF OUTPUT PARAMETERS

Input Parameters			**Output Parameters**					
Resin (%)	**Hardener (%)**	**Catalyst (%)**	**Time (sec)**	**Green Compression Strength (kg/cm2)**	**Green Shear Strength (kg/cm2)**	**Mould Hardness**	**Permeability Number**
1.00	18.00	6.00	33.51	0.36	0.52	73.33	89.74
2.00	18.00	6.00	34.67	1.20	0.80	71.67	86.74
1.00	20.00	6.00	34.05	0.90	0.57	78.33	88.32
2.00	20.00	6.00	34.90	0.75	0.38	77.67	86.17
1.00	19.00	2.00	35.38	0.70	0.77	61.67	85.00
2.00	19.00	2.00	36.13	1.00	0.35	70.00	83.23
1.00	19.00	10.00	32.53	0.85	0.45	70.00	92.44
2.00	19.00	10.00	34.75	0.90	0.68	61.00	86.54
1.50	18.00	2.00	33.92	0.80	0.32	56.00	88.66
1.50	20.00	2.00	36.46	1.11	0.22	68.33	82.48
1.50	18.00	10.00	35.58	0.80	0.46	74.67	84.52
1.50	20.00	10.00	34.38	0.79	0.78	68.33	87.47
1.50	19.00	6.00	34.60	0.88	0.37	77.67	86.91
1.50	19.00	2.00	35.00	0.35	0.25	66.67	85.92
1.50	19.00	10.00	35.35	0.79	0.34	81.67	85.07

B. Results of Output Parameter

The results for permeability, green compression, shear strength and mould hardness were obtained as shown in Table VI.

C. Analysis of Variance

To determine the parametric significance of the specified response qualities, an analysis of variance (ANOVA) was used. This study used a 95% confidence interval to determine the significance of the parametric impact. ANOVA was used to examine the design matrix created using the response surface approach. The significance of the model, the effect of process parameters, their significance, and the percentage contribution to response measures are all provided in this study.

1. Development of a Mathematical Model

The response function representing any of the output parameters can be expressed as Y = f (R, H, C). For three factors, the selected polynomial could be expressed as

$$Y = b0 + b1\,R + b2\,H + b3\,C + b11\,R*R + b22\,H*H + b33\,C*C + b12\,R*H + b13\,R*C + b23\,H*C + b113\,R*R*H + b133\,R*H*H$$

The regression equations are developed for each output parameter as follows.

Permeability = 277 - 198 Resin - 26.4 Hardener + 3.73 Catalyst + 9.3 Resin*Resin + 0.71 Hardener*Hardener + 0.0276 Catalyst*Catalyst + 19.8 Resin*Hardener + 0.184 Resin*Catalyst - 0.234 Hardener*Catalyst - 0.57 Resin*Resin*Hardener - 0.48 Resin*Hardener*Hardener

GCS = -71 + 58 Resin + 7.1 Hardener + 0.394 Catalyst + 4.3 Resin*Resin - 0.175 Hardener*Hardener + 0.0031 Catalyst * Catalyst - 6.3 Resin*Hardener- 0.0313 Resin*Catalyst - 0.0200 Hardener*Catalyst - 0.210 Resin*Resin*Hardener + 0.170 Resin*Hardener*Hardener

GSS = -25 + 18.5 Resin + 4.0 Hardener - 0.632 Catalyst + 11.99 Resin*Resin - 0.133 Hardener*Hardener + 0.00265 Catalyst * Catalyst - 3.78 Resin*Hardener+ 0.0812 Resin*Catalyst + 0.0263 Hardener*Catalyst - 0.590 Resin* Resin*Hardener + 0.140 Resin*Hardener*Hardener

Molud hardness = -952 + 39 Resin + 81 Hardener + 34.2 Catalyst - 111 Resin*Resin - 1.6 Hardener*Hardener - 0.666 Catalyst*Catalyst + 17 Resin*Hardener - 2.17 Resin*Catalyst - 1.167 Hardener*Catalyst + 5.0 Resin*Resin*Hardener - 0.83 Resin*Hardener*Hardener

2. Adequacy of the Developed Model

The developed model's adequacy was assessed using the analysis of variance technique (ANOVA). If the estimated F-ratio of the produced model does not exceed the standard tabular F-ratio for a specified degree of confidence (95%), the model may be judged sufficient within the confidence limit, according to this approach [18]. Table VII shows the results of the ANOVA.

TABLE VII ANOVA RESULTS FOR THE DEVELOPED MODEL

Model	**Permeability**	**GCS**	**GSS**	**Mould Hardness**
F-ratio	1.13	0.55	1.65	1.14
R-squared	0.99	0.83	0.97	0.99
Models	Adequate	Adequate	Adequate	Adequate

3. Direct Effect of Process Parameters

The effect of process parameters on permeability is presented in figure 8a. It is evident that as the resin increases, permeability decreases. Similarly, as the hardener increases, permeability also decreases. Initially, permeability increases with an increase in catalyst and then decreases with an increase in the catalyst.

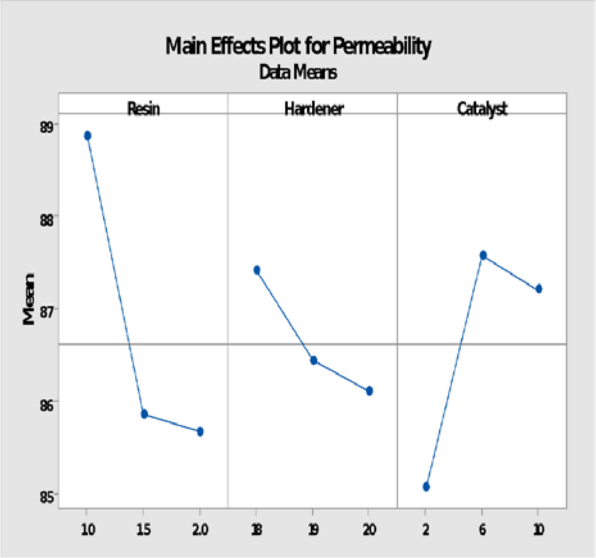

Fig. 8a Main effect plot of permeability

The effect of process parameters on green compression strength is presented in figure 8b. It is evident that as the resin increases, GCS increases.

Similarly, as the hardener increases, GCS also increases, and the same for the catalyst as well.

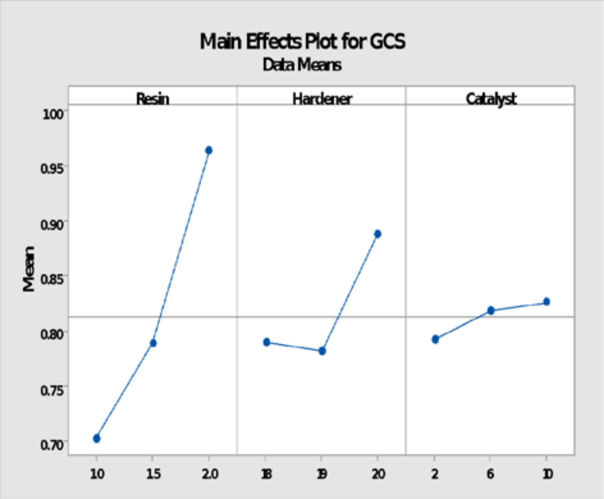

Fig. 8b Main effect plot of GCS

The effect of process parameters on green shear strength is presented in figure 8c. It is evident that as the resin increases, GSS initially decreases and after reaching 1.5 % it starts increasing. Similarly, as the hardener increases, GSS decreases and after 19 % it starts increasing. As the catalyst increases, GSS also increases.

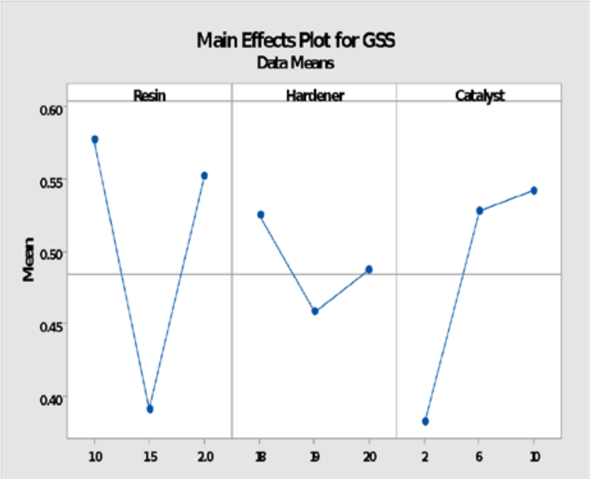

Fig. 8c Main effect plot of GSS

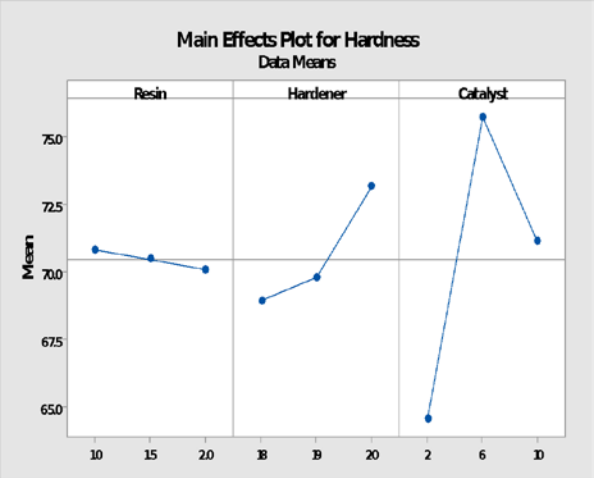

Fig. 8d Main effect plot of mould hardness

The effect of process parameters on mould hardness is presented in figure 8d. It is evident that as the resin increases, hardness starts decreasing. As the hardener increases, the mould hardness also increases. Initially, the mould hardness increases as an increase in catalyst, after reaching 6 % it starts decreasing.

D. Process Parameter Optimization

1. Optimization Using Response Surface Methodology

In all the manufacturing processes, the quality of the final product, productivity and production cost heavily depends on the values of the process parameters involved. In the case of sand casting, responses such as permeability, GCS, GSS, and mould hardness are very sensitive to the process parameters. Hence, a random selection of process parameters may lead to an increased rejection and reduction in productivity. Hence, optimization of process parameters is important. As the number of responses involved in this process is more than one, optimization considering all the responses simultaneously (multi-response optimization) or optimization of a single response function that lumps all different responses into one is the probable option. However, the single response lumped optimization usually cannot provide a set of alternative solutions that negotiate different responses against each other. On the contrary, in multi-response optimization, the interaction among different objectives gives rise to a set of compromised solutions [19].

TABLE VIII OPTIMIZATION CRITERIA FOR THE OUTPUT PARAMETERS

Response	Goal	Lower	Target
Hardness	Maximum	56.00	81.67
GSS	Maximum	0.22	0.80
GCS	Maximum	0.35	1.20
Permeability	Maximum	32.53	36.46

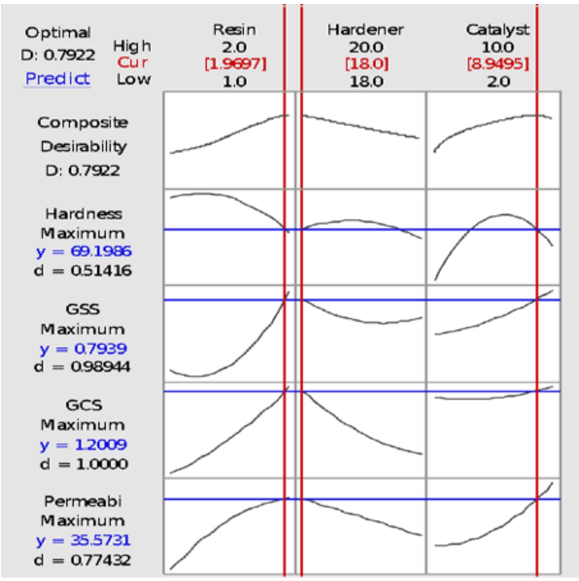

Fig. 9 Optimized process parameters using Response surface methodology

The multi-objective optimization was conducted by using the response surface optimizer module in Minitab 19. The criteria for optimization were set as shown in table VIII. The optimized results obtained are shown in table IX and the response optimizer graph is shown in figure 9.

TABLE IX OPTIMIZED EXPERIMENTAL RESULTS USING RSM

Solution	Resin	Hardener	Catalyst	Hardness Fit	GSS Fit	GCS Fit	Permeability Fit
1	1.96970	18	8.94949	69.1986	0.793875	1.20086	35.5731

IV. CONCLUSION

The following conclusions were made from the experimentation.

1. As the resin % increases from 1 % to 2 %, the permeability and mould hardness tend to decreases whereas the GCS and GSS shows the increasing trend.
2. As the hardener % increases from 18 % to 20 %, permeability and GSS decreases, whereas mould hardness and GCS increases.
3. As the catalyst % increases from 2 % to 10 %, it was observed that the permeability and hardness decreases, whereas GSS and GCC was increases.
4. From the ANOVA results, it can be concluded that there was a significant influence of input parameters on the output parameters.
5. The optimized process parameters such as 2 % of resin, 18 % of hardener and 9 % of catalyst for the Alkyd type no-bake sand casting.
6. The optimized results of the output parameters such as permeability number of 86.54, mould hardness number of 70, 1.22 g/cc of green compression strength and 0.7 g/cc of green shear strength.

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