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Optimization of investment shell mould using colloidal silica binder

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The effects of colloidal silica content, quantity of refractory filler material and the nature of electrolyte has been discussed on the properties of slurry and investment shell mould. A factorial 23 matrix was used to optimize the investment shell mould using colloidal silica binder.

In the manufacture of investment shell moulds a multi-layered investment shell is built-up by repeatedly dipping a wax pattern in a slurry thereafter draining and sprinkling with a refractory material. Each individual coat is hardened prior to applying the next coat. On achievement of the required thickness, the wax pattern is removed from the set-up and the investment shell mould is fired and poured.

Colloidal silica consists of a colloidal dispersion of virtually silica particles in water. The dispersion is stabilized by an ionic charge (sodium ion) which causes the particles to repel one another. During shell mould preparation, coherent gels in the slurry are formed by concentrating the binder[1]. The main disadvantage of colloidal silica is that its water base makes it slow drying especially in inaccessible pockets or cores[2,3]. This gives an unpredictable production schedule. The failure of colloidal silica system may also be attributed to the inadequate level (10-15%) of silica content in the binder to develop optimum strength in the investment shell mould[4,5].

Looking into the disadvantages of colloidal silica system, a basic laboratory investigation has been undertaken in the investment casting process. An attempt has also been made to increase the level of silica content to about 30% and to shorten the drying of shells by adding an accelerator to the slurry.

Experimental Procedure

In the preparation of the slurry colloidal matter content (X_1), filler to binder (F/B) ratio (X_2) and electrolyte (X_3) were used as control factors (the independent variables in the optimization method). The upper and lower levels of independent variables are given in Table 1. Slurry was prepared by adding the refractory filler (Zircon Powder) and electrolyte (ammonium acetate) to the binder liquid, using sufficient agitation to break up agglomerates and thoroughly wet and disperse the powder. Viscosity of the slurry, green and fired strength and permeability of the shell were taken as the variables (Y_1) for optimization of investment shell mould.

Viscosity test – The ford cup[6] was adjusted in the stand so that its upper edge is horizontal as shown in Fig.1. the orifice of the cup was blocked by a finger, and the cup was filled by thoroughly mixed slurry, until a convex meniscus appears above the upper edge. Excess slurry was scraped off with a straight edge. With the opening of the orifice, a stop watch was started simultaneously to measure the time from the beginning of the outflow until the first break in the stream. The kinematic viscosity was also computed[6].

Green and fired bending strength tests – Specimens for bending tests7 were made using perspex sheets of dimensions 25 mm x32 mm x 5 mm. A six-layered investment wafer was built on either side of the perspex sheet by repeatedly dipping in the slurry, draining, stuccoing and air drying. The

Table 1- Upper and lower levels of independent variables

Level	Colloidal matter, %	F/B ratio, g/cm^3	Electrolyte, %
	X_1	X_2	X_3
Upper (+)	30	3.5	0.5
Lower (-)	10	2.5	0.0

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Fig. 1- Experimental set-up for viscosity test.

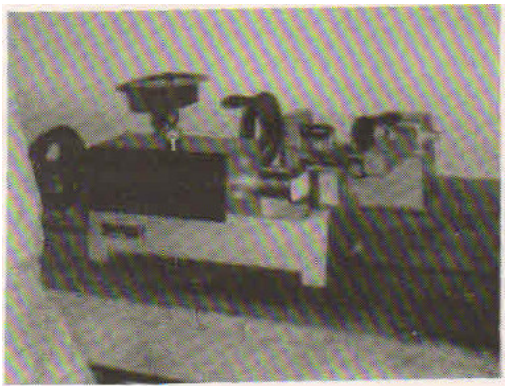

Fig. 2- Experimental set-up for bending test

Specimens were removed by surface grinding. The green bending strength of specimens was measured on a universal sand strength testing machine as shown in Fig.2. The shackles were modified to suit 25 mm x 32 mm size specimens. The fired bending strength of specimens which were fired at 800^0C for one hour and cooled to room temperature was also measured. Bending strength values were standardized using correction factor[8].

Permeability test – Specimens for permeability test were made from standard tennis balls as patterns to which a hollow brass tube of 100 mm length was fixed using M-seal. A six-layered shell was built upon the ball surface. The shells with patterns were heated up to 4000C in an oven and the plastic balls were burnout. Then, the specimen was connected, with a hose pipe to the standard permeability tester as shown

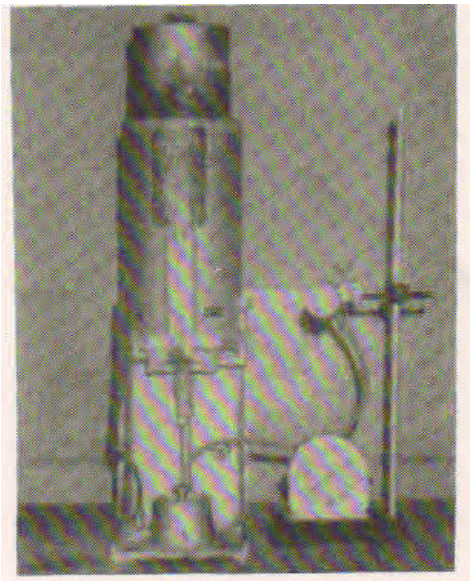

Fig.3- Experimental set up for permeability test

in Fig.3. The time taken for an air flow of 10 cm per min per sq cm was measured at room temperature, the thickness of the shell was measured using vernier calipers. The permeability number was also calculated[8].

Results and Discussion

The regression analysis is effected assuming that the optimization parameter (Y_i) is a random population normally distributed and the variance of Y_i does not depend upon its absolute value. The results of experiments are shown in Table-2.

Variance of optimization- Using the definition[9]:

$S_y^2 = \sum_{i=1}^{N} \sum_{j=1}^{n} \left(Y_{ij} - Y_i\right)^2 / N(n-1)$ the variance of optimization was computed for each parameter. The values for kinematic viscosity, green bending strength, fired bending strength and permeability are found to be 12.435, 0.022, 0.005 and 0.035, respectively. The homogeneity of variance was computed using Cochran's test[10], i.e.,

$$G = \frac{\text{macimum variance of one of the eight treatments}}{\text{the sum of all the variances for every treatment}}$$

$$= \frac{\text{Largest } S_i^2}{\sum_{i=1}^{N} \sum_{j=1}^{n} S_i^2/(n-1)}$$

where, $S_i = Y_i - \overline{Y}_i$.

The experimental values of Cochran's ratio are 0.442, 0.292, 0.32 and 0.40, respectively, for

Table 2- Results of experiments

Colloidal matter, x_1	F/B ratio, x_1	Electrolyte, x_1	Kinematic viscosity, cst		Green bending strength, N/mm^2		Green bending strength, N/mm^2		Permeability	
			Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2
+	+	+	530.00	520.62	4.82	5.09	3.56	3.64	5.42	5.18
-	+	+	300.26	294.08	3.28	3.04	2.06	2.02	6.94	6.60
+	+	-	279.08	285.24	4.44	4.62	3.50	3.37	5.68	5.61
-	+	-	130.12	132.56	2.67	2.36	1.58	1.42	9.45	9.13
+	-	+	120.84	125.43	3.05	2.82	2.06	2.08	7.57	7.49
-	-	+	72.94	70.60	2.39	2.42	1.47	1.35	10.26	10.02
+	-	-	43.56	45.72	2.66	2.84	1.75	1.85	10.04	10.00
-	-	-	32.65	34.86	2.01	2.12	1.36	1.41	10.76	10.28

Kinematic viscosity, green bending strength, fired bending strength and permeability. All these values are less than 0.6798, the tabulated value for a 2^3 matrix with two trials of each treatment. Therefore, the necessary condition for the application of regression analysis is satisfied.

Linear model- the optimization parameters, Y which is dependent on variables x_1, x_2, and x_3 may be written as,

$$Y = b_0 + b_1x_1 + b_2x_2 + b_3x_3$$

Using the least-square method, the regression coefficients may be evaluated as,

$$b_1 = \frac{\sum_{i=1}^{N}(x_{1i}-\overline{x_1})(Y_i-\overline{Y})}{\sum_{i=1}^{N}(x_{1i}-\overline{x_1})^2},$$

$$b_2 = \frac{\sum_{i=1}^{N}(x_{2i}-\overline{x_2})(Y_i-\overline{Y})}{\sum_{i=1}^{N}(x_{2i}-\overline{x_2})^2},$$

$$b_3 = \frac{\sum_{i=1}^{N}(x_{3i}-\overline{x_3})(Y_i-\overline{Y})}{\sum_{i=1}^{N}(x_{3i}-\overline{x_3})^2},$$

$$b_0 = \overline{y} - b_1\overline{x_1} - b_2\overline{x_2} - b_3\overline{x_3}$$

where, y_1 is the response in the ith treatment. For the present experimental results, the regression equations are:

Viscosity, $Y_v = 188.69 + 55.26x_1 + 120.37x_2 + 65.65x_3$

Green bending strength, $Y_t = 2.154 + 0.5716x_1 + 0.49x_2 + 0.126x_3$

Permeability, $Y_v = 8.15 - 1.03x_1 - 1.4x_2 - 0.72x_3$

Adequacy of linear model – This may be confirmed by Fisher's ratio[11]:

$$F = S_{ad}^2/S_y^2,$$

where,

S_{ad}^2 = Variance of adequacy,

$= \sum_{i=1}^{N} n(Y_i - \overline{Y_i})^2/f,$

f = the degree of freedom,

= N-K-1, for a 2^k matrix,

N = 8 and K = 3.

The experimental values of Fisher's ratio for kinematic viscosity, green bending strength, fired bending strength and permeability are 1983.75, 20.37, 79.57 and 40.09, respectively. All these values are greater than 6.09, which is the tabulated value of Fisher's ratio at 5% significance level for 4 degrees of freedom. Hence, a linear model is inadequate in all the above cases.

Non-linear model – A non-linear model with interaction of independent variables of the form:

$Y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_1x_2 + b_5x_2x_3$

$+b_6x_3x_1 + b_7x_1x_2x_3$ was considered. The non-linear regression equations obtained are:

Kinematic viscosity, Y_v

$$= 188.69 + 55.26x_1 + 120.37x_2 + 65.65x_3 + 39.55x_1x_2 + 36.52x_2x_3 + 14.59x_3x_1 + 4.57x_1x_2x_3$$

Green bending strength, Y_g

$$= 3.16 + 0.63x_1 + 0.626x_2 + 0.2x_3 + 0.324x_1x_2 + 0.069x_2x_3 - 0.05x_3x_1 - 0.009x_1x_2x_3$$

Fired bending strength, Y_f

$$= 2.154 + 0.571x_1 + 0.49x_2 + 0.615x_3 + 0.3x_1x_2 + 0.051x_2x_3 - 0.016x_3x_1 - 0.009x_1x_2x_3$$

Permeability, Y_p

$$= 8.15 - 1.03x_1 - 1.4x_2 - 0.72x_3 - 0.25x_1x_2 - 0.001x_2x_3 + 0.009x_3x_1 + 0.54x_1x_2x_3$$

The experimental values of Fisher's ratio are found to be 0.083, 0.068, 0.033 and 2.85 x 10^{-3}, respectively, for kinematic viscosity, green bending strength, fired bending strength and permeability. These values are lower than the tabulated values (6.09) of Fisher's ratio. Hence, the non-linear model is adequate.

Significance of the regression coefficients – The confidence interval Δb_j for a given parameter may be written as

$$\Delta b_j = \mathrm{tS_y}/\sqrt{\mathrm{N}},$$

Where, t is student's at a 5% significance level and S_y is the square root of variance of optimization. The values of Δb_j are 2.65, 0.111, 0.053 and 0.14 for kinematic viscosity, green bending strength, fired bending strength and permeability, respectively. The significance of the coefficients in the non-linear model is decided from the coefficients Δb_j. By retaining significant coefficients only, the final non-linear regression equations are:

Kinematic viscosity, $Y_v = 188.69 + 55.26x_1 + 120.37x_2 + 65.65x_3 + 39.55x_1x_2 + 36.52x_2x_3 + 14.59x_3x_1 + 4.57x_1x_2x_3$

Green bending strength, $Y_g = 3.16 + 0.63x_1 + 0.626x_2 + 0.2x_3 + 0.324x_1x_2 + 0.069x_2x_3$

Fired bending strength, $Y_f = 2.154 + 0.571x_1 + 0.49x_2 + 0.615x_3 + 0.3x_1x_2$

Permeability, $Y_p = 8.15 - 1.03x_1 - 1.4x_2 - 0.25x_1x_2$

Effect of silica content in the binder – The bending strength of shells increases with the growing concentration of colloidal dispersion of silica in the binder. This results from a change of the sol into gel which binds the grains of the refractory filler material of the slurry. Viscosity of the slurry increases with raising concentrations of the silicon dioxide in the binder, as silica content in the binder increases, the permeability of the shell decreases. This is owing to the formation of thicker slurry which provides less voids in the shell. The interaction of silica content in the binder with the amount of filler and electrolyte is cumulative in nature.

Effect of filler to binder ration in the slurry – Filler to binder ratio affects the character of the slurry and shell under stable concentrations of the colloidal dispersions in the binder. The slurry becomes denser as filler to binder ratio increases. Thus, viscosity and bending strength increase in proportion to the amount of filler added to the binder. The permeability of the shell decreases with increasing amount of filler in the slurry. The interaction of filler content with silica content in the binder is stronger than with electrolyte in the slurry. This is due to partial neutralization of negative charges on silicon dioxide particles by filler.

Effect of electrolyte – In colloidal silica binder, all the silica particles are negatively charged, they do not collide and stick together, because like charges repel. The electrolyte, ammonium acetate at concentration of 0.5% of the entire mixture, neutralizes all the silica

particles and makes faster gellation. Thus, ammonium acetate reduces air drying time between dip coats. Investment shells having excellent bending strengths are formed by adding ammonium acetate. Viscosity is also affected by the addition of electrolyte. Higher the electrolyte, greater the viscosity, however, permeability is not affected much by electrolyte. The interaction of electrolyte with silicon dioxide is highly commutative in nature.

Conclusion

The kinematic viscosity of slurry and bending strength of shells are increased by larger filler to binder ratio, greater silica content in the binder and by adding ammonium acetate to the slurry. The permeability of investment shell mould is not affected by electrolyte. The addition of electrolyte to the slurry reduces the air drying time between dip coats. It is suggested that the use of this colloidal silica system shortens the production cycle and provides excellent properties of the investment shell moulds.

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