Journal of Civil Engineering (IEB), 37 (2) (2009) 91-98

Journal of Civil Engineering IEB

Mix proportioning of high performance self-compacting concrete using response surface methodology

T.M. Murali and S. Kandasamy

SAI Consulting Engineers Pvt. Ltd, No 19/33, GVK Building, 10th Avenue, Ashok Nagar, Chennai 600083, Tamilnadu, India

Received on 22 January 2009

Abstract

High performance self compacting concrete (HPSCC) is typically proportioned with mineral and chemical admixtures leading to relatively high material cost. Such cost can be tolerated in high value added applications especially when cost savings can be realized using HPSCC in terms of reduction in size of reinforced concrete members. Efforts are still needed to reduce material cost of HPSCC to gain wider acceptance in variety of applications. Proper material selection and sound mixture proportioning can achieve this. The derived statistical Response Surface Methodology (RSM) is targeted to develop cost effective HPSCC mixtures. RSM can be used effectively in analyzing the cause and effect of the process parameters on response. This paper presents an experimental program in which RSM are employed to optimize a four-component concrete containing fly-ash subjected to six performances criteria. The four key mixture constituents used in the models included cement, fly-ash, and high range water reducer and water binder ratio. The modeled response that included were the compaction factor, compressive strength, split tensile strength and flexural strength at 28 days. The anticipated responses are not expected to vary in linear manner with selected variables; a central composite plan was selected to enable the model of any response in a quadratic manner. Therefore each of the four selected mixture constituents is studied in five distinct levels corresponding to codified value-2,-1,0,1,2.A total of 31 mixture combinations were used in the experimental design which consisted initially of a matrix 2^4(=16) factorial design plus seven central points and eight star points. The derived models are valid for a wide range of mixtures with ranges of water binder ratio of 0.28-0.44, cement content of 400 to 600 kg/m^3, fly-ash 0 to 10% (by weight of mass cement and HRWR dosage of 1 to 3% (by weight of mass cement).

Keywords: Self compacting concrete, mix proportioning, response surface methodology.

1. Introduction

The proportioning of concrete mixture is a process by which one arrives at the right combination of cement, aggregates, water and admixtures for making concrete according to the given specifications. The purpose of mix proportioning is to obtain a product that will perform according to certain predetermined requirements, the most essential requirements being the workability of fresh concrete and the strength and durability of the hardened concrete.

Another purpose of mix proportioning is to obtain a concrete mixture satisfying the performance requirements at the lowest possible cost by selecting available materials. The partial replacement of binder by fly-ash results in the reduction of heat of hydration without any reduction in strength (Jones 2002).

The aim of mix proportioning exercise is to achieve a set of critical properties at optimum cost and to enhance the performance of concrete for non-critical properties. Mix proportioning is not unique, because all parameters are not practically measurable and are not amendable to mathematical manipulation.

Mixture proportion selection for HPSCC is often most well handled by using systematic optimization processes and methods of experimental design (Hansen 1997). An attempt has been made in this experimental investigation to formulate a procedure for mix proportioning of HPSCC using a statistical method called RSM.

RSM is a set of techniques that encompasses:

- Designing of a set of experiments for adequate and reliable measurement of the true mean response.
- Determining the mathematical model with best fit.
- Finding the optimum set of experimental factors that produces maximum and minimum value of the response.
- Representing the direct and interactive effect of the process parameters.

2. Objectives and scope

This paper presents and examines the mix proportioning of HPSCC using RSM technique.

- To optimize the HPSCC mixture proportions.
- Development of mathematical model for desired properties of concrete strength like compressive, tensile, flexural and workability in terms of process control parameters.
- To study the influence of process parameters on responses.
- Total percentage of deviations between the observed values and the values computed from the models.
- Relation between the process control parameters and responses.

3. Experimental Design

3.1 Materials

Ordinary Portland cement of 53 grade as per IS 12269, obtained from a local cement-manufacturing factory having a specific gravity of 3.15 was used. Locally available river sand confined to IS 383-1970 having fineness modulus of 2.6 and specific gravity of 2.68 and locally available blue granite as per IS 383-1970 passing through 16mm sieve with a specific gravity 2.6 and fineness modulus of 5.65 was used. Flay-ash contains extremely fine amorphous particles of SiO_2.The specific gravity and bulk density of fly-ash used is 2.2 and 280kg/m^3. The superplasticizer used in this study is CONPLAST – SP337 (SNF) of specific gravity 1.2.

3.2 Identification of Process Control Parameter

Process control parameters listed in Table 1

Variables

Binder (Kg/m^3)	B
Water –Binder ration (No Unit)	W/B
Fly Ash (%)	F
Superplasticizer (%)	S

Constants

Fine Aggregates	660-720 kg/m^3
Coarse Aggregates	1100 kg/m^3

Table 1
Process control parameters under limits

Parameters	Units	Notations	Limits				
			-2	-1	0	1	2
Binder	Kg/m^3	B	400	450	500	550	600
Water Binder ratio	No unit	W/B	0.28	0.32	0.36	0.40	0.44
Fly-Ash	%	F	0	2.50	5.002	7.50	10.0
Super Plasticizer	%	S	1.00	1.50	.00	2.50	3.00

3.3 Finding the limits of the process control variables

The working range was decided based upon the strength aspects of HPSCC. The coded forms of process control parameters were found by fixing the values for central parameter (0), maximum (+2) and minimum (-2) value of the variable. The coded values were calculated from the following relationships:

$$X_i = 2[2X – (X_{max} + X_{min})] / (X_{max} – X_{min})$$

where,

X_i = Required coded value of a variable X

X = Any value of the variable form Xmin to Xmax

The conversions between coded and absolute values can be calculated as follows:

$$\text{Coded B} = \frac{|B| - 500}{45}$$

$$\text{Coded W/B} = \frac{|W/B| - 0.36}{0.04}$$

$$\text{Coded F} = \frac{|F| - 5.0}{2.5}$$

$$\text{Coded S} = \frac{|S| - 2}{0.5}$$

3.4 Developing the design matrix

The design matrix was developed using the software called SYSTAT 10.2. This software increases the analytical power with more statistics by delivering extensive list of algorithms. It also visualizes the data provided with more graphing capabilities. SYSTAT 10.2 offers a large variety of scientific and technical graphs for a desktop statistics package. The selected design matrix shown in Table 2 is a central composite rotatable factorial design consisting of 31 set of coded values. It comprises of a full replication of 2^4 (=16) factorial design plus seven center points and eight star points. All the variables at the intermediate level (0) constitute the highest (+2) level with other three variables at the intermediate levels constituting the star points. Thus the 31 experimental run allowed the estimation of the linear, quadratic and two-way interactive effect of the process parameters.

Table 2
Design matrix in coded form and observed values of the responses

Mix No.	Design Matrix in Coded Form				Measured Responses			
	B	W/B	F	S	C	T	F	X
1.	-1	-1	-1	-1	69.91	4.750	7.84	0.89
2	1	-1	-1	-1	77.63	6.465	8.77	0.86
3	-1	1	-1	-1	65.20	4.756	7.68	0.92
4	1	1	-1	-1	72.51	5.980	7.75	0.89
5	-1	-1	1	-1	80.92	6.570	8.452	0.86
6	1	-1	1	-1	87.24	6.820	8.46	0.83
7	-1	1	1	-1	74.14	6.350	8.618	0.89
8	1	1	1	-1	75.42	6.370	8.194	0.86
9	-1	-1	-1	1	71.73	6.250	7.940	0.92
10	1	1	-1	1	80.14	8.530	8.50	0.89
11	-1	1	-1	1	70.81	4.720	7.69	0.94
12	1	1	-1	1	73.84	6.300	7.90	0.92
13	-1	-1	1	1	81.32	6.620	8.83	0.89
14	1	-1	1	1	94.14	7.020	8.92	0.86
15	-1	1	1	1	75.93	5.480	8.22	0.92
16	1	1	1	1	79.20	6.530	9.34	0.89
17	-2	0	0	0	65.30	4.280	6.33	0.90
18	2	0	0	0	73.71	7.240	8.93	0.83
19	0	-2	0	0	72.40	6.300	8.05	0.83
20	0	2	0	0	67.26	5.120	7.26	0.92
21	0	0	-2	0	63.55	4.310	7.86	0.86
22	0	0	2	0	74.63	5.400	8.01	0.84
23	0	0	0	-2	72.52	4.400	8.46	0.83

Mix No.	Design Matrix in Coded Form				Measured Responses			
	B	W/B	F	S	C	T	F	X
24	0	0	0	2	71.70	4.880	7.8	0.88
25	0	0	0	0	69.00	4.460	7.53	0.867
26	0	0	0	0	68.20	5.680	6.98	0.85
27	0	0	0	0	69.10	5.640	7.90	0.87
28	0	0	0	0	68.90	5.060	7.63	0.86
29	0	0	0	0	68.15	5.720	7.00	0.79
30	0	0	0	0	68.84	5.930	7.24	0.86
31	0	0	0	0	68.32	5.710	7.72	0.79

C: Compressive Strength in N/mm^2; T= Tensile strength in N/mm^2; F: Flexural Strength in N/mm^2; W= Workability (CF); Mix no. 25-31 were cast in different time intervals.

3.5 Recording of responses

The ingredients for the various mixes were weighed and mixing was carried out using pan type concrete mixer. Precautions were taken to ensure uniform mixing of ingredients. The specimen were cast in steel moulds and compacted on a table vibrator. 100 mm cube specimens were cast for the determination of compressive strength at 28 days. 100x100x500 mm beam specimens and 100mm diameter x 200mm long cylinder specimens were cast for the determination of flexural and split tensile strength at 28 days respectively. Curing of specimen was started as soon as the top surface of the concrete in the mould was stiff (hard) enough. Spreading wet gunny bag over the moulds was carried out for the initial curing. 24 hours after the casting, the specimen were demoulded and placed immediately in water tank for further curing. Compaction factor test were carried out as per the IS specification to find out the workability of concrete.

3.6 Development of mathematical model

The response function representing any of the recorded responses of HPSCC can be expressed as:

$$Y = f(B, W/B, F, S)$$

The relationship selected being a second-degree response surface expressed as follows

Y = b0+b1B+b2 F/B +b3F+b4 S+b11 B2 +b22 W/B. W/B +b33 F.F +b44 S.S+b12
B. W/B +b13 B.F +b14 B.S +b23 W/B.F +b24 W/B.S +b34 F.S

The values of the coefficients were calculated by regression analysis using SYSTAT 10.2 software.

3.7 Final Mathematical Model

The values of the regression coefficient give an idea as to what extent the control variables affect the responses quantitatively. In significance coefficient using student t-test can be dropped along with responses to which they are associated without affecting much of the accuracy of the model. As per this test, when the calculated value of t corresponding to a coefficient exceeds the standard tabulated value for the desired level of confidence (say 95%) the coefficient becomes significant. The significant regression coefficient tabulated in Table 3 was recalculated and the final models were developed using only these significant coefficients:

The final models for the various responses as determined by the above analysis are represented below:

C = 68.630 + 2.791B-2.761W/B + 3.696F + 1.343B.B + 1.424W/B.W/B + 1.239 F.F + 1.994S.S 1.274B.W/B – 1.367 W/B.F

T = 5.431 + 0.6.2 B – 0.371 W/B + 0.258 F + 0.181 S + 0.242 B.B + 0.229 W/B.W/B + 0.317 B.F – 0.265 W/B.S – 0.269 F.S

F = 7.429 + 0.323B – 0.162 W/B + 0.220F +0.131 B.B + 0.137B.B + 0.137 W/B.W/B + 0.206 F.F + 0.256 S.S

W = 0.841 - 0.015B + 0.017 W/B – 0.011 D + 0.014 S + 0.011 B.B + 0.013 W/B.W/B + 0.007 F.F +0.008 S.S

Table 3
Estimated Values of Coefficients of the Models

Coefficient		Compressive strength in 28 days N/mm^2 R^2=0.75	Tensile strength in 28 days N/mm^2 R^2=0.60	Flexural Strength in 28 days N/mm^2 R^2=0.60	Workability C.F R^2=0.70
b0	Mean	68.630	5.431	7.429	0.841
b1	B	2.791	0.602	0.323	-0.015
b3	W/B	-2.761	-0.371	-0.162	0.017
b4	F	3.696	0.258	0.220	-0.011
b11	S	-	0.181	-	0.014
b22	B.B	1.343	0.242	0.131	0.011
b33	W/B	1.424	0.229	0.137	0.013
b44	F.F	1.239	-	0.206	0.007
b12	S.S	1.994	-	0.256	0.008
b13	B.W/B	-1.274	-	-	-
b14	B.F	-	-0.317	-	-
b23	B.S	-	-	-	-
b24	W/B.F	-1.367	-	-	-
b34	W/B.S	-	-0.265	-	-
	F.S	-	-0.269	-	-

R^2 = Coefficient of determination.

The validity of the above equation can be judged from the coefficient of determination Table 3 between the experimental values and calculated values obtained from the response surface equation. The mathematical model furnished above can be used to predict the proportions of HPSCC mix constituents by substituting the value in coded form, of the respective factors.

4. Results and discussions

4.1 Effect of fly-ash on the fresh properties of concrete

The water demand of concrete containing fly-ash increases with increasing amount of fly-ash. The increase is primarily due to the high surface area of the fly-ash. Fresh concrete containing fly-ash is more cohesive and less prone to segregation. As the fly-ash content increased, the concrete may appear to become sticky. Concrete containing fly–ash normally does not segregate appreciably because of the fineness of the fly-ash and the use of HRWRA.

Concrete containing fly-ash shows significantly reduced bleeding. This effect is primarily by the high surface area of the fly-ash to be wetted; there is very little water left in the mixture for bleeding. The colors of the fresh and hardened concretes containing fly-ash are generally darker than the conventional concrete.

From Table 2 it was found that the optimum replacement of fly-ash for getting strength of 90Mpa is 7.5%. As the compressive strength increases, the tensile and flexural strength of the concrete also increases but at a gradually decreasing rate.

5. Conclusion

Based on the experimental investigation the following conclusions are drawn within the limitations of the test results.

- Statistical experimental design can be used to systematically investigate the selected range of combination of ingredients for the desired characteristics.
- The mathematical models furnished in this investigation can be used to predict the proportions of various constituents of concrete, by substituting the value, in coded form, of respective factors.
- The five level factorial techniques can be employed easily for developing mathematical model for predicting the strength and workability within the workable region of control parameters for required characteristics.
- Optimum binder composition concrete mixtures for the designed strength can be identified from the proposed models.
- RSM can be used effectively in analyzing the cause and effect of the process parameters on response.
- A combination of 7.5% SF and 2.5% SP was the optimum dosage of admixtures for obtaining high strength concrete of 90 Mpa.

References

ACI Committee 234 R-96 (2003), "Guide for the silica fume in concrete", ACI manual of concrete practices, pp 234 R-1 to 46.

ACI committee 304R-00 (2003), "Guide for measuring, mixing, transporting and placing concrete", ACI manual of concrete practices, pp 304R-1 to 39.

Cohran.G and Cox.M. "Experimental Designs", Asia Publishing House India, 1963.

Hansen, M.R, James.R.Demaro, (1997). “HPC mixture proportion optimization for precast concrete using statistical”, Proceedings of the international symposium on HPC, New Orleans, Lousiane.

Ghezal A. and Kamal.H.Khyat (2002). “Optimizing Self Consolidating Concrete with Limestone Filler by Using Statistical Factorial Design Methods” ACI Materials Journal, 99, May-June 2002.

IS 456-2000. “Plain and Reinforced Concrete-code of Practice”, BIS, New Delhi, India.

IS 516-1959. “Method of Test for Strength of Concrete”, BIS, New Delhi, India

IS 5816-1970. “Method of Test for Splitting Tensile Strength of Concrete Cylinders”, BIS, New Delhi, India.

Jones.M.R and Magee.B.J, (2002). “A Mix constituent proportioning method for concrete containing ternary combinations of cements”, Magazine of Concrete Research, 54, No.2, April, pp 125-139

SYSTAT 10.2- Systat software Asia Pacific Limited, Bangalore.