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Response surfaces for compressive strength of concrete

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HIGHLIGHTS

- ▶ Desirabilities of responses govern the choice of effect variables in mix design.
- ▶ Desirabilities of variables should be taken into consideration in optimization.
- ▶ Separate evaluations of categoric effect variables increases the power of model.
- ▶ The range of each effect variable is of crucial importance in elimination process.
- ▶ Significance of a model term must be assessed based on the attribute it represents.

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ABSTRACT

The aim of total quality management (TQM) is to offer satisfactorily high quality products to customers for providing increased productivity and decreased costs. Various methods are used for process improvement, development and optimization. In ready mixed concrete production, the number and the variations of effect parameters can be reduced using response surface methodology.

In this study, firstly influence levels of the main and interaction terms of effect variables were determined using 2^{7-3} fractional factorial design in order to reduce the number of simultaneously controllable variables. Then, quadratic terms were determined using D-Optimal design, and response surface graphics were plotted.

1. Introduction

The aim of total quality management (TQM) applied in different fields of industry is to offer products of sufficiently high quality to costumers by increasing productivity and decreasing costs. Various methods (response surface methodology (RSM), Taguchi designs, designs for second order model, optimal designs, mixture designs, etc.) are used for process improvement, development, optimization and ultimately quality improvement as one of the managerial principles of TQM framework also in cement and concrete industry [1,2].

In 1997, Simon et al. [3] described a method for determining high performance optimized concrete mix proportions with six constituents (namely, water, superplasticizer, cement, silica fume, fine and coarse aggregates) subject to several performance constraints using statistical mixture experiments. Numerous researchers used mixture design and response surface methodology in their investigations [4–12].

For adequate optimization the main, quadratic and interaction terms of influence levels of controllable variables on concrete compressive strength are to be determined and response surfaces must be established in ready-mixed concrete production where there are a large number of effect parameters. Therefore, in this study 2^{7-3} fractional factorial design was used in order to reduce the number of simultaneously controllable variables and influence levels of the main (x_1, x_2, etc.), quadratic (x_1^2, x_2^2, etc.) and interaction ($x_1 \cdot x_2$ etc.) terms were determined using D-Optimal design obtained by the augmentation of 2^{7-3} fractional factorial design. Influence levels and response surface graphics of controllable variables were obtained using "Design-Expert Version 7.1 [13]" computer program.

2. Experimental program

In view of the large number of parameters effective in the production of ready mixed concrete, the aim of this experimental program is, firstly, to reduce the number of simultaneously controllable variables affecting the compressive strength of concrete,

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Nomenclature

ANOVA	analysis of variance (–)
AT	aggregate type (–)
CC	cement content (kg/m$^{3)}$
CV	coefficient of variation (%)
df	degrees of freedom (–)
$D_{\max}$	maximum aggregate particle size (mm)
f_c	compressive strength of concrete (MPa)
f_{cc}	compressive strenght of cement (MPa)
Id	identification number for each experimental condition (–)
k	fineness modulus (–)
k_k	fineness modulus of aggregate mix (–)
$P_{a \leqslant 4.00\ \mathrm{mm}}$	fine aggregate volume fraction passing 4.00 mm mesh sieve (%)
PRESS	predicted residual sum of squares (–)
SP	superplasticizer dosage by mass of cement (%)
Std	standard order (–)
$R2$	coefficient of multiple determination (–)
W/C	water/cement (%)
x	variable (–)
α	significance level (–)
μ	water absorption (kg/kg)
ρ	particle density (kg/m^3)
σ	blaine specific surface (m^2/kg)

and, secondly, to establish actual response surface graphics by obtaining the influence levels of the main, quadratic and two factor interaction terms of controllable variables.

2.1. Methodology

Experimental design was performed in two stages separately as a 2^{7-3} fractional factorial design and a D-Optimal design for 11.2 mm and 22.4 mm maximum aggregate sizes. A fractional factorial design is generated from a full factorial experiment by choosing an alias structure. The alias structure determines which effects are confounded with each other. 2^{7-3} fractional factorial design is a "Resolution IV Designs" in which no main effect is aliased with any other main effect or with any two-factor interaction, but two-factor interactions are aliased with each other [2]. In general, a design that minimizes the variance of the model regression coefficients is called a D-Optimal design and these designs are found by selecting run in the design to maximize the determinant of moment matrix.

Simultaneously controllable variables and variation intervals taken into consideration in the 2^{7-3} fractional factorial design and the D-Optimal design are given in Tables 1 and 2, respectively.

Estimation and aliased terms to obtain by Design Expert 7.1 programs used in 2^{7-3} fractional factorial design are given in Table 3. The additional estimation terms to be used in D-Optimal design were determined as A^2, B^2, D^2, E^2, ABC and A^{2}C.

Each point of run (sample) consisting of 3 specimens of 150 mm-cube, in total 276 (138 + 138) cube compressive strength specimens were produced in 2^{7-3} fractional factorial design, and in total 66 (36 + 30) cube specimens were produced in D-Optimal design for additional run points. In total 342 cube specimens were produced and all the specimens were cured in water at 20 °C ± 2 °C during 28 days.

2.2. Materials

Properties of constituent materials used are given in Table 4, and the aggregate grading curves are shown in Fig. 1. Aggregate fineness moduli are determined on a 13 test sieve set (0.063–0.125–0.250–0.500–1.0–2.0–4.0–5.6–8.0–11.2–16.0–22.4–31.5-mm mesh).

3. Experimental results

Design summary for 2^{7-3} fractional factorial design are shown in Table 5. Factor values and compressive strength results at run points for $D_{\max}$ = 11.2 mm and $D_{\max}$ = 22.4 mm are given in

Table 1
Simultaneously controllable variables in 2^{7-3} fractional factorial design.

No	Factor	Name	Units	Variation intervals	
				$D_{\max}$ = 11.2 mm	$D_{\max}$ = 22.4 mm
1	*A*	Water/cement (W/C) ratio	%	55–60	50–55
2	*B*	Cement content (CC)	kg/m^3	330–345	330–345
3	*C*	Compressive strength of cement (f_{cc})	MPa	34.4–55.1	34.4–55.1
4	*D*	Fineness modulus of the aggregate mix (k_k)	–	5.6–5.8	6.6–6.8
5	*E*	Fines content ($P_{a \leqslant 4.00\ \mathrm{mm}}$) of the aggregate mix	vol.%	65–68	48–54
6	*F*	Admixture (superplasticizer, SP) dosage	mass% of cement	1.2–1.4	1.2–1.4
7	*G*	Aggregate type (AT)	Type	Limestone–Basalt	Limestone–Basalt

Table 2
Simultaneously controllable variables in D-Optimal design.

$D_{\max}$ = 11.2 mm			$D_{\max}$ = 22.4 mm		
No	Factor	Name	No	Factor	Name
1	*A*	Water/Cement (W/C) ratio	1	*A*	Water/Cement (W/C) ratio
2	*B*	Cement content (CC)	2	*B*	Cement content (CC)
3	*C*	Compressive strength of cement (f_{cc})	3	*C*	Compressive strength of cement (f_{cc})
4	*D*	Fines ($P_{a \leqslant 4.00\ \mathrm{mm}}$) content of the aggregate mix	4	*D*	Mix aggregate Fineness modulus of the aggregate mix (k_k)
5	*E*	Admixture (superplasticizer, SP) dosage	5	*E*	Admixture (superplasticizer, SP) dosage
6	*F*	Aggregate type (AT)	6	*F*	Aggregate type (AT)