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Modeling the polypropylene fiber effect on compressive strength of self-compacting concrete

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Abstract. Although the self-compacting concrete (SCC) offers several practical and economic benefits and quality improvement in concrete constructions, in comparison with conventionally vibrated concretes confronts with autogenously chemical and drying shrinkage which causes the formation of different cracks and creates different problems in concrete structures. Using different fibers in the mix design and implementation of fibrous concrete, the problem can be solved by connecting cracks and micro cracks together and postponing the propagation of them. In this study an experimental investigation using response surface methodology (RSM) based on full factorial design has been undertaken in order to model and evaluate the polypropylene fiber effect on the fibrous self-compacting concrete and curing time, fiber percentage and fiber amount have been considered as input variables. Compressive strength has been measured and calculated as the output response to achieve a mathematical relationship between input variables. To evaluate the proposed model analysis of variance at a confidence level of 95% has been applied and finally optimum compressive strength predicted. After analyzing the data, it was found that the presented mathematical model is in very good agreement with experimental results. The overall results of the experiments confirm the validity of the proposed model and this model can be used to predict the compressive strength of fibrous self-compacting concrete.

Keywords: SCC; polypropylene fiber; compressive strength; RSM; modeling

1. Introduction

The use of self-compacting concrete (SCC) has spread throughout the world since the first developments in the 1980s due to the ease of production and high performance of the final product. The advantages of SCC have been widely shown in a large amount of research and publications which were reviewed by Almeida *et al.* (2010). But SCC is a brittle material with a low strain capacity. Reinforcement with short randomly distributed fibers can address some of the concerns related to SCC brittleness and poor resistance to crack growth. Fibers, used as reinforcement, can be effective in arresting cracks at both micro and macro-levels. At the micro-level, fibers inhibit the initiation and growth of cracks, and after the micro-cracks coalesce into macro-cracks, fibers provide mechanisms that abate their unstable propagation, provide effective

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bridging, and impart sources of strength gain, toughness and ductility (Oucief *et al.* 2006, Bentur and Mindess 1990, Balaguru and Shah 1992).

Polypropylene has a hydrophobic surface that prevents it from being wetted by the cement paste. Since they are non-polar the bundles of polypropylene fibers do not cling or ball together (Brown *et al.* 2002, Hannant 1978). The hydrophobic nature of the polypropylene fiber does not affect the mixing water requirements of the concrete (Brown *et al.* 2002, Association PC 1998). Also they have excellent chemical resistance at room temperature. It has excellent abrasion resistance due to the surface smoothness. The fibers do not react to any substances that can form stains and they have good wash ability. The growth of microorganisms does not affect the mechanical properties of fibers (Brown *et al.* 2002, Hannant 1978, Association PC 1998, Clive *et al.* 1998, Balaguru and Slattum 1995). They also exhibit very good chemical inertness but they degrade from exposure to UV light (Brown *et al.* 2002, Clive *et al.* 1998, Balaguru and Slattum 1995). Hence, in this study polypropylene fiber is selected to investigate its effects on SCC and model the empirical results using response surface methodology (RSM).

RSM is a collection of mathematical and statistical techniques that is useful for the modeling, analyzing, and optimizing of objects in which a response of interest (typically a property) is influenced by several parameters (Azadbeh *et al.* 2014, Mohammadzadeh *et al.* 2014, Montgomery DC 2008). RSM also quantifies the relationship between the controllable input parameters and the obtained responses (properties). The steps in this method involve: designing a series of experiments for adequate and reliable measurement of the response of interest, determining a mathematical model of the second-order response surface with the best fit, finding the optimal set of experimental parameters that produce a maximum or minimum value of response and representing the direct and interactive effects of process parameters through two and three dimensional plots (Azadbeh *et al.* 2014, Mohammadzadeh *et al.* 2014, Montgomery DC 2008).

RSM was developed by Box and Wilson (Box *et al.* 1978, Lovato *et al.* 2012), and first applied in chemical engineering and later in other areas of knowledge such as chemistry, physics, clinical and engineering science (Lovato *et al.* 2012). This technique is relatively new to civil engineering and has been used less in comparison with other sciences. Research works in concrete technology is similar to chemical and material engineering and experiment planning and analysis techniques are used to improve the characteristics of product and process quality, to reduce the number of tests and to optimize the use of resources (materials, time, equipment availability, etc.) (Lovato *et al.* 2012).

For assessment and modeling of parameters influencing different types of concrete, very little research has been done by response surface methodology. Outstanding among them are the efforts of (Lovato *et al.* 2012, Del Coz Diaz *et al.*2014, Guneyisi *et al.* 2014, Cihan *et al.* 2013, Cai *et al.* 2013, Aldahdooh *et al.* 2013, Mohammed *et al.* 2012, Nambiar and Ramamurthy 2006, Bayramov *et al.* 2004). Cihan *et al.* (2013) used RSM for optimizing compressive strength and reducing the number of simultaneously controllable variables with six constituents (namely, water/cement ratio, cement content, compressive strength of cement, fineness modulus of the aggregate mix, fines content of the aggregate mix, admixture dosage, aggregate type). Bayramov *et al.* (2004) optimized the fracture parameters of steel fiber reinforced concretes to obtain a more ductile behavior than that of plain concrete using this methodology. Aldahdooh *et al.* (2013) evaluated ultra-high-performance-fiber reinforced concrete binder content using the response surface method as well. In this study, for the first time effect of polypropylene fibers on the compressive strength of SCC using this method is discussed. Three variables namely curing time, fiber length and fiber

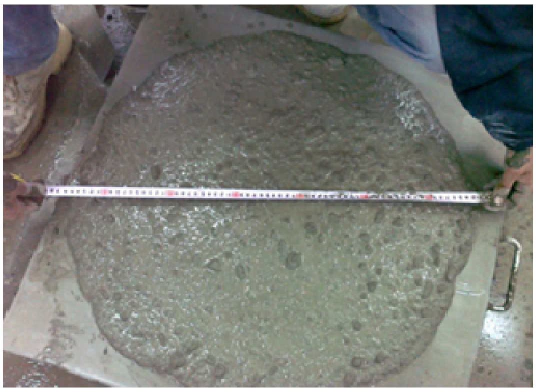

Fig. 1 Slump-flow test

Fig. 2 V-funnel test

Fig. 3 L-box test

percentage were used as input parameters and compressive strength was selected as an output parameter. The experiments were designed using RSM based on full factorial design and analysis of variance (ANOVA) was applied for checking the adequacy of the proposed model. Finally the effect of input variables on the compressive strength was evaluated using contour plots and the optimum condition was predicted.

2. Experimental work

This research includes seven series of mix designs with different aspect ratio and percentage of polypropylene fibers. One of the series were specimens made without any fibers as control samples and in the next six mixes, specimens were made with two size of polypropylene fibers of 6 and 12 mm with fibers dosage of 0.05, 0.1 and 0.15% as weight percentages of cementitious material. For each mix, samples of 150×300 mm cylinders were prepared and cured for 7,14 and 28 days in fresh water until the date of test. The concrete was mixed using a pan type mixer, placed in cylindrical 150×300 mm oiled metal moulds.

At first, it was assumed that the fibers would lower the workability of the mixtures: for this reason the control mixtures were proportioned at the upper level of self-compatibility, in order to remain within the given limits after the addition of the fibers. Slump flow, V-funnel and L-box

Table 1 Fresh properties of SCC mixes

	Control Samples	Fibrous SCC- 6 mm-0.05%	Fibrous SCC- 6 mm-0.10%	Fibrous SCC- 6 mm-0.15%	Fibrous SCC- 12 mm-0.05%	Fibrous SCC- 12 mm-0.10%	Fibrous SCC- 12 mm-0.15%
Slump-flow test (mm)	600	590	570	530	600	550	520
T500 (sec)	2	2.2	2.7	2.9	2.3	2.9	3.3
V-funnel test (sec)	3	3.4	4.3	5	3.6	4.9	6.5
L-box test	0.92	0.90	0.86	0.80	0.88	0.85	0.77
V-funnel test after 5 min (sec)	5	7	9.2	9.8	8.6	10.4	12.8

Table 2 The raw materials used in the presented mixture design

Materials	Kg/m^3
Water	190
Cement	350
Silica fume	30
Sand	920
Coarse Aggregate size I	555
Coarse Aggregate size II	300
Sand powder	20
Superplasticizer	5.7
Polypropylene fiber content	0.19-0.38-0.76

Table 3 Conformity of proportions of this research and proportions of EFNARC (2005)

Constituent	Typical range by mass (kg/m^3)	Typical range by volume (liters/m^3)	Proportions of this research	conformity
Powder	380 - 600		400	✓
Paste		300 - 380	361	✓
Water	150 - 210	150 - 210	190	✓
Coarse aggregate	750 - 1000	270 - 360	855	✓
Fine aggregate (sand)	Content balances the volume of the other constituents, typically 48 – 55% of total aggregate weight.		51.83%	✓
Water/Powder ratio by Vol		0.85 – 1.10	1.07	✓

tests are performed to assess workability (Figs.1, 2 and 3).

Control mixes were designed based on the suggested key factors recommended by The European Guidelines for self-compacting concrete (2005). The result of self-compacting characteristic tests of control samples were listed Table 1.

2.1 Materials and mix proportions

In this study, an attempt has been made to use regional materials. Materials used include aggregates, cementitious materials (cement and pozzolans), water, industrial-chemical additives, filler, polypropylene fibers from Isfahan factory in different sizes including 6 and 12 mm. Maximum aggregate size was 19 mm. Stone powder was used as a mineral viscosity enhancing admixture with a specific gravity of 2.65 and dosage of 20 kg/m^3. Thus, in all mix designs,

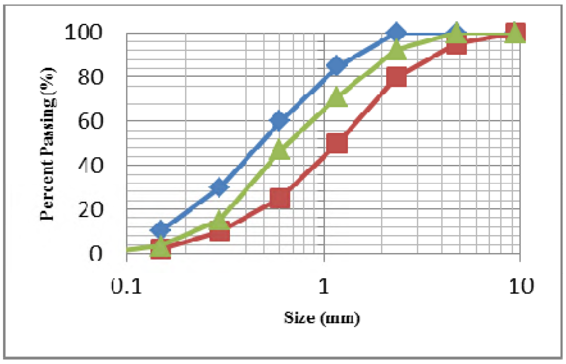

Fig. 4 Grading curve of sand after correction

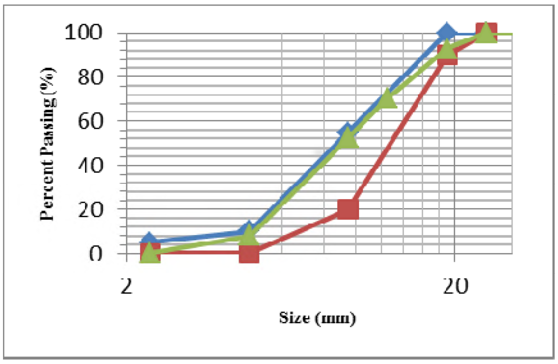

Fig. 5 Grading curve of coarse aggregate

Table 4 Physical properties of polypropylene fibers

Specific gravity	0.91
Diameter	22 mm
Width crossing	Circular
Melting point	160-170 °C
Water absorption	0
Color	white

water/powder ratio has been kept constant in 0.47. The raw materials used in the presented mixture design were listed in Table 2, where it is in agreement with Table 8.2 in European Guidelines for SCC (2005). In European Guidelines for self-compacting concrete (Table 8.2, 2005) has been given as an indication of the typical range of constituents in SCC by weight and by volume and those proportions mentioned in this table are in no way restrictive and many SCC mixes will fall outside this range for one or more constituents. But the mix design proportions of this research are exactly in range presented by EFNARC (2005). Proportions of this research and proportions of EFNARC are compared in Table 3.

2.1.1 Cementitious materials

Type II Portland cement from Iran-Soufian Cement Co. was used in this research. The cement content used in experiment was 380 Kg/m^3 out of which 7.8% was replaced with silica fume.

2.1.2 Aggregate

Gravel with the maximum size of 19 mm and sand grains with maximum size of 4.75 mm were used as aggregates. Natural aggregates and sand were prepared from Aji Chay River in Tabriz, Iran. Based on grading curve of sand it was identified that Fineness modulus (FM) of sand was 3, so it was required that the grading curve of sand be corrected and amount of FM was reduced to 2.76. Grading curves of fine and coarse aggregates are presented in Figs.4 and 5. Sand powder passed from NO.100 sieve with amount of 20 kg/m^3 is used as a mineral viscosity enhancing admixture and also this amount of powder increases fineness of sand.

2.1.3 Polypropylene fiber

Polypropylene fibers from Isfahan factory in different sizes including 6 and 12 mm Prepared. The physical properties of polypropylene fibers are presented in Table 4.

Table 5 Coded values of key effective parameters

Symbols	Variables	Coded values of variables				
		-1	-0.33	0	0.33	1
A	Curing Time (day)	7	-	14	-	28
B	Fiber Length (mm)	6	-	-	-	12
C	Fiber Percentage (%)	0	0.05	-	0.10	0.15

Table 6 Design layout using the Design-Expert 8.0 software including experimental and predicted results for compressive strength

Standard order	Runs	Values of parameters			Compressive Strength [kg/cm^2]	
		A	B	C	Actual values	Predicted values
1	5	7	6	0.00	238.50	230.32
2	23	14	6	0.00	305.00	300.58
3	13	28	6	0.00	419.00	420.97
4	3	7	12	0.00	238.50	246.67
5	22	14	12	0.00	305.00	314.43
6	19	28	12	0.00	419.00	429.82
7	24	7	6	0.05	245.00	261.49
8	9	14	6	0.05	321.50	326.04
9	8	28	6	0.05	424.50	435.00
10	16	7	12	0.05	270.50	266.03
11	6	14	12	0.05	377.50	328.07
12	17	28	12	0.05	463.00	432.04
13	12	7	6	0.10	268.50	260.21
14	14	14	6	0.10	330.00	319.04
15	15	28	6	0.10	428.50	416.58
16	20	7	12	0.10	235.00	252.93
17	11	14	12	0.10	274.00	309.26
18	1	28	12	0.10	370.50	401.80
19	10	7	6	0.15	231.00	226.47
20	4	14	6	0.15	262.00	279.59
21	7	28	6	0.15	368.50	365.70
22	21	7	12	0.15	224.50	207.37
23	2	14	12	0.15	260.00	257.99
24	18	28	12	0.15	348.00	339.10

2.1.4 Superplasticizer

In this research superplasicizer (SP) based on modified polycarboxilate has been used and its consumption rate is 0.6 to 1.2 weight percentage of cement consumption whereas the consumption rate recommended by manufacture of this SP for production of SCC is 1 to 2 weight percentage of cement consumption.

3. Modeling

3.1 Response surface methodology

Design of experiments is an empirical and analytical technique for setting effective process parameters (those which have a significant effect on the response of interest). Factorial design and RSM are the most applicable methods in design of experiments. A RSM advanced technique known as User-Defined design was applied for full factorial experiments with numerical and discrete parameters in order to evaluate mathematical model for response and optimize the variables.

Hence, in this study, response surface method based on a full factorial design was used to investigate the effect of polypropylene fibers on SCC. Parameters including Curing time, fiber length and fiber percentage was considered as a variable. Values of the variables and how they change as real and coded values have been presented in Table 5. The measured response parameter was the compressive strength of SCC. The results obtained through the experiments and predicted model are summarized in Table 6. The available data have been analyzed by RSM using Design-Expert 8.0 software.

3.2 Development of mathematical model

In this study, amount and fiber percentage were mathematically related to the empirically obtained response function (compressive strength of SCC). The developed model can predict mechanical properties of fabricated specimens. A second order polynomial regression model has been developed for evaluation of effects of all parameters. The response is a function of fiber length (A, mm), fiber percentage (B, %) and curing time (C, day) that can be expressed as follows

$$Y = f(A, B, C) \tag{1}$$

Where Y is a response value. The second order regression equation using in this research to represent the response surface for k factors is given by

$$Y = a_0 + \sum_{i=1}^{k} a_i k_i + \sum_{i=1}^{k} a_{ii} X_i^{\,2} + \sum_{i \langle j} a_{ij} X_i X_j \tag{2}$$

Where X_i and X_j are the coded independent variables, a_0 is the free term of the equation and a_i, a_{ii} and a_{ij} are linear, quadratic, and interaction constant coefficients, respectively (Mohammadzadeh *et al.* 2014). The selected polynomial could be expressed as

$$Y = a_0 + a_1 A + a_2 B + a_3 C + a_{12} AB + a_{13} AC + a_{23} BC + a_{11} A^2 + a_{22} B^2 + a_{33} C^2 \tag{3}$$

Where the letters A, B, and C represent the factors in the model and combinations of factors (such as AB) represent an interaction between the individual factors in that term. The values of the equation Eq. (3) were calculated by the regression method using the Design-Expert 8.0 software at 95% confidence level using the following expressions (Azadbeh *et al.* 2015)

$$a_0 = 0.142857(\sum Y) - 0.035714 \sum \sum (X_{ii} Y) \tag{4}$$

$$a_i = 0.041667 \sum (X_i Y) \tag{5}$$

$$a_{ii} = 0.03125\sum(X_{ij}Y) + 0.00372\sum\sum(X_{ii}Y) - 0.035714(\sum Y) \quad (6)$$

$$a_{ij} = 0.0625\sum(X_{ij}Y) \quad (7)$$

The stationary or optimum points (points where the slope of response surface is zero with respect to any independent variable) may represent a point of maximum or minimum or a saddle point, hence it can be written

$$\frac{\partial Y}{\partial A} = \frac{\partial Y}{\partial B} = \frac{\partial Y}{\partial C} = 0 \quad (8)$$

The values of the independent parameters at the optimum value of response ($Y_{opt.}$) can be denoted as A^*, B^*, and C^* and $Y_{opt.}$ can be written as follows (Azadbeh *et al.* 2015)

$$Y_{opt.} = f(A^*, B^*, C^*) \quad (9)$$

The regression coefficients of the second order polynomial regression model were calculated from the experimental data shown in Table 6. Also, in order to ensure the model accuracy, ANOVA analysis was performed including tests for significance of the regression model and coefficients.

4. Results and discussion

4.1 Modeling of compressive strength

Response surface second order mathematical model using Design Expert software was developed for compressive strength of SCC in terms of coded values effective parameters according to Table 5. The suggested mathematical model is given in equation below

$$\begin{aligned} &Compressive\ Strength\ [Kg/cm^2] = 352.36 + 80.59A - 2.56B - 23.64C \\ &-1.87AB - 12.86AC - 8.86BC - 7.55A^2 - 36.52C^2 \end{aligned} \quad (10)$$

According to model coefficients it is concluded that effective parameters has different effects on compressive strength. From A and C coefficients it is obvious that the curing time and fiber percentage have the most significant effect on achieving higher compressive strength. For better evaluation of the effect of effective parameters on the compressive strength, detailed studies have been undertaken using perturbation and contour plots in next parts.

4.2 Model adequacy checking

In order to check if the control variables and their interactions have been significant or not, a variance analysis (ANOVA), normality, and regression analysis were carried out for response variable, considering a confidence interval of 95%.

Table 7 presents the ANOVA and the adequacy of the developed model. It can be easily found that the second order model, which was developed to predict the compressive strength, coincides well with the observed data.

Table 7 ANOVA table for the response

Source	MS	F-value	P-value
Model	15219.34	29.35	<0.0001
A	1.04E+05	200.44	<0.0001
B	154.83	0.3	0.5928
C	7321.27	14.12	0.0019
AB	58.33	0.11	0.742
AC	1523.81	2.94	0.107
BC	1047.25	2.02	0.1757
A^2	231.44	0.45	0.5142
B^2	-	-	-
C^2	6321.26	12.19	0.0033
Residual	518.48	-	-
R^2	0.9400	-	-
Adj. R^2	0.9079	-	-

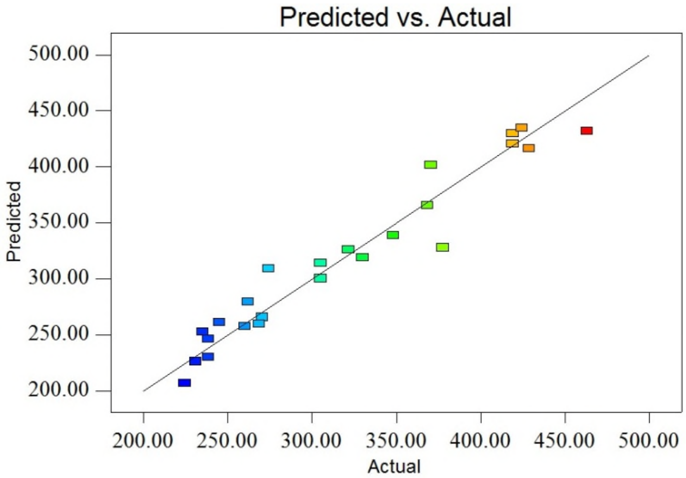

Fig. 6 Graph of the predicted response values versus the actual response values

The F-value is the ratio of the model mean square (MS) / residual MS and shows the relative contribution of the model variance to the residual variance. A large number indicates more of the variance being explained by the model; a small number says the variance may be more due to noise (Azadbeh *et al.* 2015). The model *F*-value (model MS/residual MS) of 29.35 implies the developed model is significant. *P*-value is the probability value that is associated with the *F*-value for this term. It is the probability of getting an *F*-value of this size if the term did not have an effect on the response. *P*-values of less than 0.05 indicate that the model terms are significant. Values above 0.1 indicate that the model terms are not significant. In general, a larger *F*-value and smaller *P*-value indicate a more significant model and its coefficients. In this case *A*, *C* and *C*2 are significant model terms. The determination coefficient *R*2, which is a commonly used criterion to decide whether a fitted regression model is appropriate, for the response is equal to 0.94. Since R2 always increases as any terms are added to the model, some regression model builders prefer to

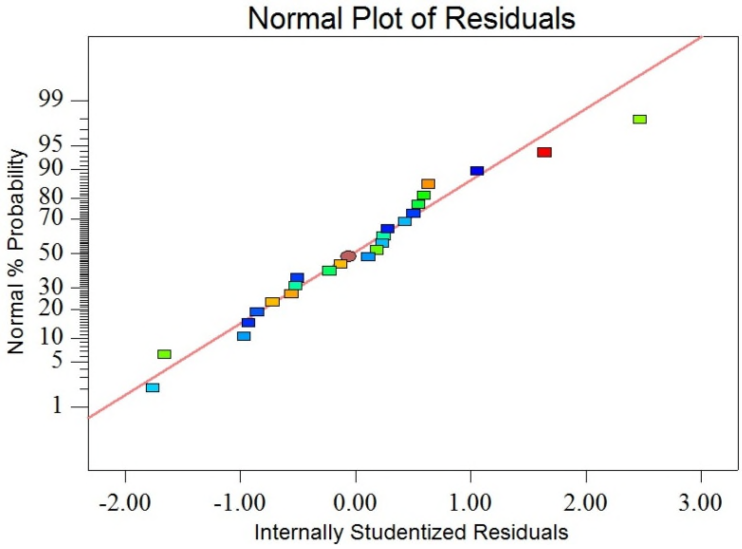

Fig. 7 Normal probability plot of residuals for responses

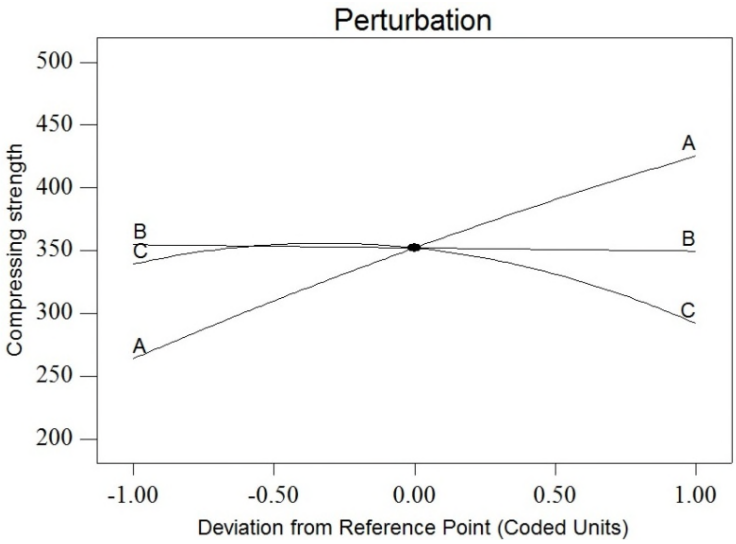

Fig. 8 Perturbation plot at the central points of the design space compressive strength

use an adjusted R^2 statistic. In general, the adjusted R^2 statistic will not always increase as variables are added to the model. In fact, if unnecessary terms are added, the value of adjusted R^2 will often decrease (Myers and Anderson-Cook 2009). Here adjusted R^2 for compressive strength is equal to 0.9079. It is clear that R^2 and adjusted R^2 are not differing dramatically and the models do not have unnecessary terms. It may be concluded that the prediction made by these developed models complies well with the experimental observations. Fig. 6 is the distribution diagram of forecast value and actual value (Predicted vs Actual), where its data are mainly in a straight line. Fig. 7 is the normal probability distribution diagram of residual, where all data are mainly in a straight line, and it is obvious that errors are spread normally.

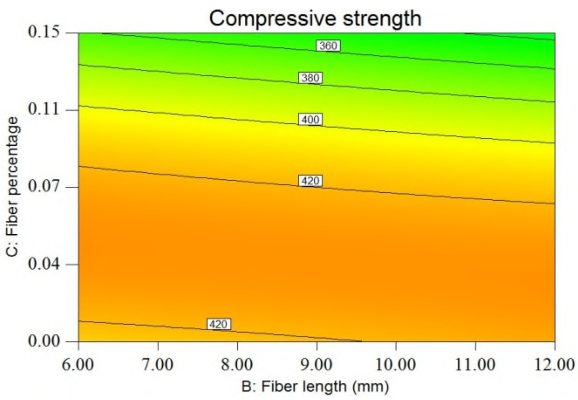

Fig. 9 Contour plot of interaction between fiber percentage and fiber length

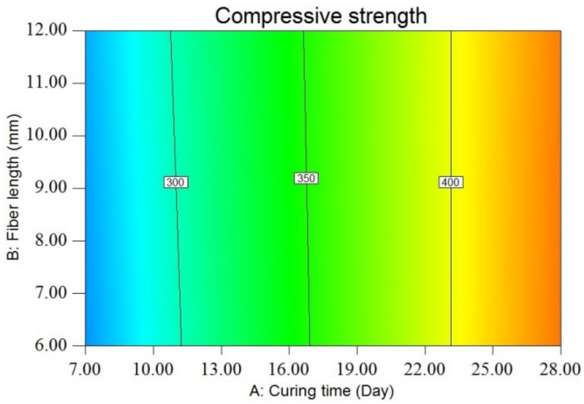

Fig. 10 Contour plot of interaction between curing time and fiber length

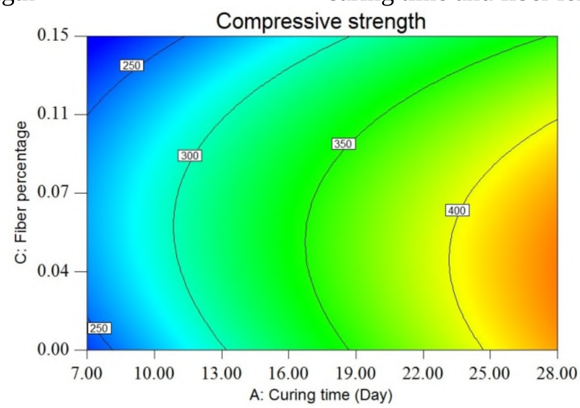

Fig. 11 Contour plot of interaction between curing time and fiber percentage

4.3 Influence of effective parameters on compressive strength

Perturbation plots can provide a sight to compare the effect of all effective parameters at particular points of the design space. This plot is presented in Fig. 8 at the central point of the design space. It shows the change in compressive strength while each effective parameters move from the reference point, when all other parameters are held constant at the reference value. The line with a slope close to zero shows fiber length does not have much effect on compressive strength (*B* curve). Assuming the fiber length and curing time to fix at center point, the impact of changes in fiber percentage can be observed (curve *C*). The effect of fiber percentage on compressive strength has a parabolic behavior and in middle parts of the curve it has a maximum value; therefore it is observed that the optimum amount of fiber is about 0.05 percent. As shown by curve *A*, it can be seen that curing time has parabolic behavior on strength as well; increasing curing time causes more compressive strength. It should be mentioned that parabolic curve *A* seems like a straight line because it has a large concavity.

To explore the effects of parameters considering the interaction between the parameters, two-dimensional contour curves of compressive strength can be utilized. According to Figs. 9-11, using two-dimensional contour plots it can be observed that the maximum compressive strength (28 days) is obtained approximately in 0.05% when the interaction between the lengths of the fiber is

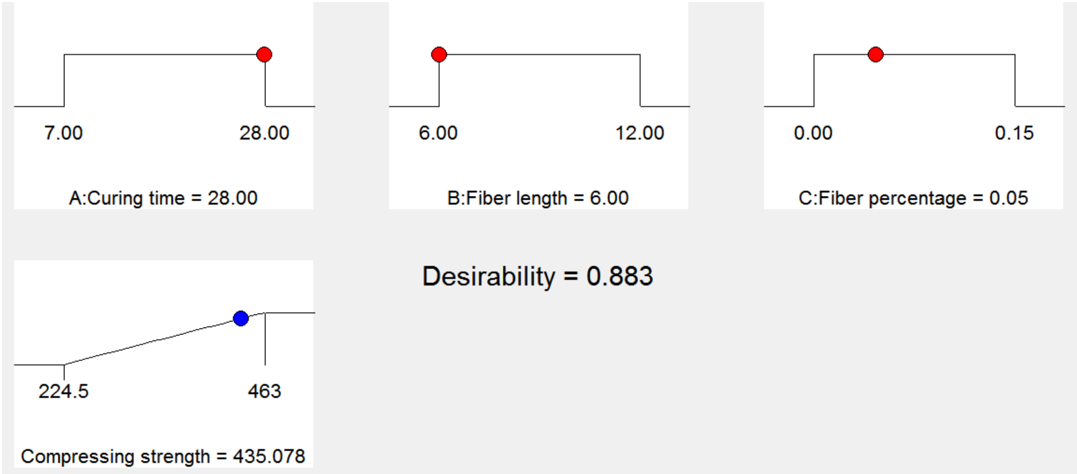

Fig. 12 Ramp view for parameters and response

considered. As mentioned in the previous section, fiber length has little effect on the compressive strength; this issue can also be derived from the contour plot drawn for the interaction of fiber amount and length (Fig. 9).

Contour plot for the fiber length and curing time (Fig. 10) shows that the compressive strength almost depends only on curing time and also fiber and curing time shows the parabolic behavior of fiber length on compressive strength.

4.4 Optimizing process

One important advantage of response surface method is optimization of the studied system. To obtain optimal conditions using design expert software, values of the response variables were obtained according to results of the ANOVA table and two-dimensional contour diagrams. Fig. 12 shows the ramps function graph for the optimum condition. The ramps view shows the desirability for each parameter and each response, as well as the combined desirability. A highlighted point shows both the exact value of the parameter or response (horizontal movement of the point) and how well that goal was satisfied (how high up the ramp) (Mozammel *et al.* 2015). It can be seen that by assuming maximum amount of compressive strength at optimal value, the proposed condition with a desirability of 1.000 is as follow: fiber percentage: 0.05%, fiber length: 6 mm and curing time: 28 day.

5. Conclusions

In this study an experimental investigation using response surface methodology (RSM) based on full factorial design has been undertaken in order to model and evaluate the polypropylene fiber effect on the fibrous SCC and curing time, fiber percentage and fiber amount was considered as input variables. Compressive strength was measured and calculated as the output response to achieve a mathematical relationship between input variables. To evaluate the proposed model analysis of variance at a confidence level of 95% was applied and finally optimum compressive strength predicted. After analyzing the data, the following remarks can be highlighted.

• Mathematical models at 95% confidence level for compressive strength of fibrous SCC is obtained using response surface methodology based on full factorial design and ANOVA results confirmed the validity of the proposed model.

• Two-dimensional diagrams were demonstrator of parabolic behavior of fiber amount and also semi-linear (parabolic behavior with large concavity) behavior of curing time on compressive strength.

• Changes in fiber length have almost no effect on the compressive strength of polypropylene fiber reinforced SCC.

• Adding fiber to concrete specimens in the mix increases the compressive strength and its reason probably can be interpreted due to reducing micro-cracks in transition zone of concrete.

• Maximum compressive strength was obtained for fiber length of 12 mm and fiber percentage of 0.05 that in this case the amount of increased strength is about 10.5%.

• Adding too much fiber causes decreasing of compressive strength of SCC because high fiber content decreases workability and flowability of SCC and increases the amount of tapped air in concrete

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