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Statistical models for mechanical properties of UHPC using response surface methodology

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Abstract. One of the main disadvantages of Ultra High Performance Concrete exists in the large suggested value of UHPC ingredients. The purpose of this study was to find the models mechanical properties which included a 7, 14 and 28-day compressive strength test, a 28-day splitting tensile and modulus of rupture test for Ultra High Performance Concrete, as well as, a study on the interaction and correlation of five variables that includes silica fume amount (SF), cement 42.5 amount, steel fiber amount, superplasticizer amount (SP), and w/c mechanical properties of UHPC. The response surface methodology was analyzed between the variables and responses. The relationships and mathematical models in terms of coded variables were established by ANOVA. The validity of models were checked by experimental values. The offered models are valid for mixes with the fraction proportion of fine aggregate as; 0.70-1.30 cement amount, 0.15-0.30 silica fume, 0.04-0.08 superplasticizer, 0.10-0.20 steel fiber, and 0.18-0.32 water binder ratio.

Keywords: response surface method; ultra high performance concrete; compressive strength; splitting tensile strength; modulus of rupture; central composite method

1. Introduction

Attention to the mechanical properties of concrete for higher strength and ductility and also the increase in its durability has resulted in the innovation for several types of concrete. It could be said that; Ultra high performance concrete is one of the latest concrete with unique properties such as high compressive strength, exhibiting tensile and flexural strength with increase in energy absorption (Mosaberpanah and Eren 2016), high durability, improved resistance against freezing-thawing and various chemical attacks (Wang 2014). UHPC represent the highest development of high performance concrete in different curing conditions (Mohammed *et al.* 2014).

Despite increasing the concretes performance, the concrete performing in terms of CO_2 emissions and environmental effects should be considered more. In these decade, global warming and other significant ecological changes are increasing (Mosaberpanah and Eren 2016). For producing UHPC a large amount of binder or cement is required which has been reported by researchers to be more than 1000 kg/m^3 (Rahdar and Ghalehnovi 2016). Whereas, manufacturing 1 ton of cement produces approximately 900 kg/m^3, finding the optimum amount of cement is significantly meaningful. Although some investigations showed some solution by cement replacement without significant decrease in performance (Yu *et al.* 2014, Alqadi *et al.* 2013).

Response surface methodology (RSM) is a combination between mathematical and statistical techniques, it can be used for modeling and analyzing several variables which gives a good interpretation by finding the relationship between variables to achieve the optimum response (Lotfy *et al.* 2015). Although, there are many methods which find the mix proportion, for instance, Sebaibi *et al.* (2013) which made use of particle packing model found the mix proportion.

Aldahdooh *et al.* (2013) reported using RSM within 2 variables for evaluating UHPC binder content. In this research the RSM used for modeling and optimizing the mechanical properties of UHPC in normal curing and local materials with 5 variables are w/c, SF amount, cement amount, Steel fiber amount, and, superplasticizer.

2. Experimental activities

2.1 Materials

2.1.1 Cement

The type 2 Portland sulfate resistance slag cement of 42.5 was used to produce UHPC. Specification of cement used controlled by European standard cement composition (EN197-1). The amount of slag was between 21-35% and clinker was between 65-79% for manufacturing the cement in Cyprus.

2.1.2 Fine aggregate

In this study, lime stone sand with maximum diameter of 5 mm was used. Sieve analysis was carried out based on standard ASTM C136 and also controlled by standard

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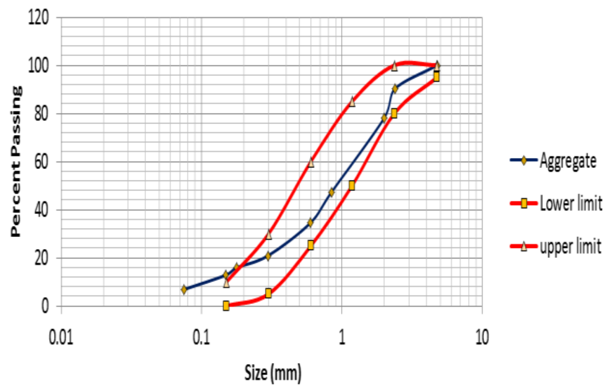

Fig. 1 Sieve analysis of lime stone

ASTM C33 as shown in Fig. 1.

2.1.3 Mixing water

The mixing water was ordinary tap water.

2.1.4 Superplasticizer

Polycarboxylic ether based with high range water reducing agent was used as superplasticizer in this study. The new generation superplasticizer admixture with the name of GLENIUM 27 was produced by BASF. The superplasticizer is consistent based on EN 934-2.

2.1.5 Silica fume

A white undensified silica fume with more than 95% purity of silicon dioxide and with particle sizes between 0.1-1 μm was used as pozzolanic material.

2.1.6 Steel fiber

The diameter of steel fiber was 0.55 mm and 13 mm in length with tensile strength of 1345 MPa and young modulus of 210 GPa.

2.2 Experimental design

Design of experiment was done by using response methodology. In this study the mechanical properties of UHPC was analyzed and the relation between variables were considered.

2.3 Methodology

In this research, based on RSM, the mechanical properties of UHPC with local materials at different levels as well as mix proportion for each responses were considered and the interaction of variables was monitored. The response surface modeling used was central composition design with α=1 (face centered) and linear or quadratic models for responses. The interaction between variables and the effect on responses were analyzed by ANOVA. The statistical software "Design-Expert version 9.0.3", Stat-Ease, Inc., was used to analyze the experimental design.

In this study, the mechanical properties of UHPC was investigated as: the 7 days compressive strength, 14 days compressive strength and 28-day compressive strength as well as splitting tensile and flexural strength test were denoted as responses and 5 variables that includes silica fume (A), superplasticizer (B), steel fiber (C), cement (D), w/c ratio (E) were defined to explain the modeling. The variable ranges are as follow: SF amount from 15 to 30 percent, the superplasticizer content from 4 to 8 percent, the steel fiber content from 10 to 20 percent, the cement amount from 70 to 130 percent (all the proportions are by lime stone weight) and water binder ratio from 0.18 to 0.32. The range of variables are given in Table 1.

Table 1 The variables ranges

Variables	Assigned	Levels of Variables		
		-1	0	+1
Silica fume	A	15%	25%	30%
Superplasticizer	B	4%	6%	8%
Steel fiber	C	10%	15%	20%
Cement	D	70%	100%	130%
W/C Ratio	E	0.18	0.22	0.32

*All the proportions are the fraction of lime stone weight

2.4 Specimen preparation and test specimen

In this study, 45 batches totally were sampled which is shown in Table 2, which the mortar mixed in drum rotating mixer. First premix was included by dry materials (cement, silica fume, lime stone) were blended for 5 minutes, then superplasticizer was added to water as well as steel fiber, thereafter, mix of water, superplasticizer, and steel fiber was added to premixed mixture and blended to obtain homogeneous paste. Ten cubes with dimensions of 100 mm×100 mm were casted for compressive strength test. Also, three 10×20 (D×L) cylinders were casted for 28 days splitting tensile strength test, and finally three 10×10×50 beams were used for 28 days flexural strength test. After molding, all specimens were compacted by vibration table and kept in moist curing room for 24 hours. They were then de-molded and transferred to curing water tank at 23±2℃.

2.5 Compressive strength test

To find out the compressive strength of samples, 100 mm UHPC cubes were experienced. Universal machine with the capacity of 3000 kN was carried out by following ASTM C109. Three specimen were tested. The range of compressive strength were obtained from 41 to 95 MPa for 7-day, 45.3 to 103 MPa for 14-day, and, 47 to 110 MPa for 28-days.

2.6 Tensile strength test

Two types of tension tests were implemented to find tensile strength in UHPC which were flexural testing and splitting tensile test of cylinders.

2.7 Flexural strength test

The ASTM C1018 was used for this test. This test

Table 2 Design of experiments

Mix no	SF A	SP B	Fiber C	Cement D	w/c E	Sand	SF A	SP B	Fiber C	Cement D	w/c E
1	-1	1	-1	-1	1	1	0.15	0.08	0.10	0.7	0.32
2	1	-1	-1	1	1	1	0.30	0.04	0.10	1.3	0.32
3	1	-1	1	-1	-1	1	0.30	0.04	0.20	0.7	0.18
4	0	0	1	0	0	1	0.20	0.06	0.20	1.0	0.22
5	1	-1	-1	-1	-1	1	0.30	0.04	0.10	0.7	0.18
6	0	0	0	0	-1	1	0.20	0.06	0.15	1.0	0.18
7	-1	1	-1	-1	-1	1	0.15	0.08	0.10	0.7	0.18
8	1	-1	1	1	-1	1	0.30	0.04	0.20	1.3	0.18
9	-1	0	0	0	0	1	0.15	0.06	0.15	1.0	0.22
10	-1	-1	1	-1	1	1	0.15	0.04	0.20	0.7	0.32
11	0	-1	0	0	0	1	0.20	0.04	0.15	1.0	0.22
12	1	1	-1	1	1	1	0.30	0.08	0.10	1.3	0.32
13	0	0	0	1	0	1	0.20	0.06	0.15	1.3	0.22
14	1	-1	1	-1	1	1	0.30	0.04	0.20	0.7	0.32
15	1	-1	1	1	1	1	0.30	0.04	0.20	1.3	0.32
16	-1	-1	-1	1	1	1	0.15	0.04	0.10	1.3	0.32
17	0	0	0	0	1	1	0.20	0.06	0.15	1.0	0.32
18	-1	-1	1	1	1	1	0.15	0.04	0.20	1.3	0.32
19	-1	-1	-1	1	-1	1	0.15	0.04	0.10	1.3	0.18
20	0	0	0	0	0	1	0.20	0.06	0.15	1.0	0.22
21	1	-1	-1	-1	1	1	0.30	0.04	0.10	0.7	0.32
22	0	0	0	0	0	1	0.20	0.06	0.15	1.0	0.22
23	-1	1	-1	1	1	1	0.15	0.08	0.10	1.3	0.32
24	1	1	1	1	-1	1	0.30	0.08	0.20	1.3	0.18
25	1	1	1	1	1	1	0.30	0.08	0.20	1.3	0.32
26	-1	1	1	-1	-1	1	0.15	0.08	0.20	0.7	0.18
27	-1	-1	1	1	-1	1	0.15	0.04	0.20	1.3	0.18
28	-1	-1	1	-1	-1	1	0.15	0.04	0.20	0.7	0.18
29	1	1	-1	-1	-1	1	0.30	0.08	0.10	0.7	0.18
30	1	1	1	-1	1	1	0.30	0.08	0.20	0.7	0.32
31	-1	-1	-1	-1	-1	1	0.15	0.04	0.10	0.7	0.18
32	1	1	1	-1	-1	1	0.30	0.08	0.20	0.7	0.18
33	1	-1	-1	1	-1	1	0.30	0.04	0.10	1.3	0.18
34	-1	-1	-1	-1	1	1	0.15	0.04	0.10	0.7	0.32
35	1	1	-1	1	-1	1	0.30	0.08	0.10	1.3	0.18
36	-1	1	1	1	1	1	0.15	0.08	0.20	1.3	0.32
37	-1	1	1	-1	1	1	0.15	0.08	0.20	0.7	0.32
38	-1	1	-1	1	-1	1	0.15	0.08	0.10	1.3	0.18
39	1	1	-1	-1	1	1	0.30	0.08	0.10	0.7	0.32
40	0	1	0	0	0	1	0.20	0.08	0.15	1.0	0.22
41	1	0	0	0	0	1	0.30	0.06	0.15	1.0	0.22
42	0	0	0	-1	0	1	0.20	0.06	0.15	0.7	0.22
43	0	0	-1	0	0	1	0.20	0.06	0.10	1.0	0.22
44	0	0	0	0	0	1	0.20	0.06	0.15	1.0	0.22
45	-1	1	1	1	-1	1	0.15	0.08	0.20	1.3	0.18

involves four point flexural loading. The beam size was 100×100×500 mm with the span of 300 mm and load distance of 100 mm.

2.8 Splitting tensile strength

Splitting tensile was performed through the ASTM C496 Standard test method for splitting tensile strength of cylindrical concrete specimens. The specimen was 100×200 mm (d×L) cylinder at 28 days. Standard concrete compression machine was used to do this experiment.

3. Results

The effects of five variables (silica fume, superplasticizer, steel fiber, cement, and w/c) on the mechanical properties (compressive and tensile strength) of UHPC have been analyzed by using response surface method.

Table 3 shows the amount of materials used in each mixture batch within results of using five different variables in mechanical properties of UHPC, compressive strength in 7, 14, and 28-day, splitting tensile, and modulus of rupture. Each outcome was derived by average of 3 specimens.

The interaction and correlation between variables and responses was calculated by ANOVA analysis of variance. For the modeling, linear model, two-factor interaction, and quadratic models were considered to find best predictive model. In each model, the significant parameters were detected and then, by backward elimination technique the insignificant terms were eliminated and the final regressions for each were performed. Consequently, the quadratic model was selected for all responses. The quality of prediction models were determined by coefficient of multiple determination R^2, which shows the total deviation of the variables from the prediction model. The p-value (probability of errors) with 95% confidence level and statistical significant test at 5% and also lack of fit with p-value greater than 0.05 was performed for model validations.

Table 4 shows, all quadratic models were significant according to t-test ($P<0.05$) and F-value of 13.44, 14.19, 15.43, 11.74, and 13.10 and lack of fit with given P-value implies which are insignificant. In addition, the model coefficient of determination R^2 has a reliable confidence with 0.87, 0.88, 0.88, 0.88, and 0.83 for the different responses. The predicted R^2 of 0.7, 0.73, 0.75, 0.67, and, 0.69 are in reasonable agreement with adjustment in R^2 of 0.81, 0.82, 0.82, 0.81, and 0.77 for all responses, whereas, the differences is less than 0.2.

The performance of offered prediction models with mechanical responses (7, 14, and 28 days compressive strength, splitting tensile strength, and rupture module) for mixture experimental design of UHPC are illustrated in Fig. 2.

Tables 5 and 6 listed the finalized prediction models to reach the desired performance of compressive and tensile strength of UHPC in terms of real mixture ingredient. Probability factor is given for each parameter, in Table 5, it is clear that linear B, C, and, D which have high P-value are not statistically significant factors at the stipulated

Table 3 Mix design and responses of UHPC

Mix no	Sand (kg)	Silica Fume (kg) A	Super plasticizer (kg) B	Steel fiber (kg) C	Cement (kg) D	Water (kg) E	Compressive strength (MPa)			Tensile (MPa) Y4	Rupture (MPa) Y5
							7 Y1	14 Y2	28 Y3		
1	50	7.5	4	5	35	13.6	58.0	65.0	71.0	5.5	7.0
2	50	15	2	5	65	25.6	42.0	48.0	49.0	4.0	4.9
3	50	15	2	10	35	9.0	88.5	96.3	103.2	9.0	11.46
4	50	10	3	10	50	13.5	75.0	86.0	97.0	10.0	10.5
5	50	15	2	5	35	9.0	87.0	91.0	97.0	9.0	11.1
6	50	10	3	7.5	50	10.8	66.0	91.0	102.0	6.0	6.6
7	50	7.5	4	5	35	7.6	77.8	91.0	102.0	6.1	8.5
8	50	15	2	10	65	14.4	95.0	103.0	110.0	5.5	8.75
9	50	7.5	3	7.5	50	12.9	81.5	94.0	106.0	6.2	8.3
10	50	7.5	2	10	35	13.6	76.0	83.0	85.0	5.4	7.0
11	50	10	2	7.5	50	13.5	71.5	80.8	83.4	5.0	7.5
12	50	15	4	5	65	25.6	64.5	74.6	77.0	3.5	4.0
13	50	10	3	7.5	65	16.8	72.2	81.5	86	5	9.47
14	50	15	2	10	35	16.0	42.6	53.3	57.35	4.6	7.33
15	50	15	2	10	65	25.6	41	45.3	47	3.9	6.27
16	50	7.5	2	5	65	23.2	67	72	81.5	4.6	5
17	50	10	3	7.5	50	19.2	73.1	85.3	93.5	4.72	9.255
18	50	7.5	2	10	65	23.2	61.3	67.5	71.7	4.9	10.74
19	50	7.5	2	5	65	13.0	85	99.5	104.5	6.2	11.25
20	50	10	3	7.5	50	13.5	61.6	67.1	73	4.56	7.84
21	50	15	2	5	35	16.0	44.8	56	63.6	4.6	7.2
22	50	10	3	7.5	50	13.5	76	80	86	5.1	9.56
23	50	7.5	4	5	65	23.2	69	80	82	4	5
24	50	15	4	10	65	14.4	78	85	93	7	10
25	50	15	4	10	65	25.6	56.2	64.1	70.8	4.72	7.61
26	50	7.5	4	10	35	7.6	74	79	82.9	6.4	11.64
27	50	7.5	2	10	65	13.0	94.6	97	105.8	8.5	12.14
28	50	7.5	2	10	35	7.6	91.3	101	109	10.2	15
29	50	15	4	5	35	9.0	80	87	99	5.13	7
30	50	15	4	10	35	16.0	66.6	73.5	85	5	6.6
31	50	7.5	2	5	35	7.6	83	94	109	8	12.4
32	50	15	4	10	35	9.0	76	79.5	87	8.5	9.31
33	50	15	2	5	65	14.4	75.9	94.8	95.7	4.96	9.37
34	50	7.5	2	5	35	13.6	54	58.7	68.9	5.2	7.7
35	50	15	4	5	65	14.4	72	80	88	4.4	8.4
36	50	7.5	4	10	65	23.2	62.5	75.5	87	5.52	5.67
37	50	7.5	4	10	35	13.6	67.4	73	79	5.25	9.24
38	50	7.5	4	5	65	13.0	89	92.2	93.9	4.71	9.61
39	50	15	4	5	35	16.0	61.1	72	86	5.5	6.97
40	50	10	4	7.5	50	13.5	73	83	86	4.5	7
41	50	15	3	7.5	50	14.6	73.5	85	95	5	7
42	50	10	3	7.5	35	10.1	70	79	83	6.5	8.886
43	50	10	3	5	50	13.5	73.7	84	95.2	7	8.541
44	50	10	3	7.5	50	13.5	70	76	82	5.4	11.03
45	50	7.5	4	10	65	13.0	75.8	86	91.3	5.44	9.47

Table 4 Analysis result of regression models

Response	R^2	Adj-R^2	Pre-R^2	F-Value	Lack of fit	Model P-value
Compressive strength 7 days	0.87	0.81	0.70	13.44	0.81	<0.0001
Compressive Strength 14 days	0.88	0.82	0.73	14.19	0.61	<0.0001
Compressive strength 28 days	0.88	0.82	0.75	15.43	0.54	<0.0001
Splitting tensile strength	0.88	0.81	0.67	11.74	0.3	<0.0001
Modulus of Rupture	0.83	0.77	0.69	13.10	0.92	<0.0001

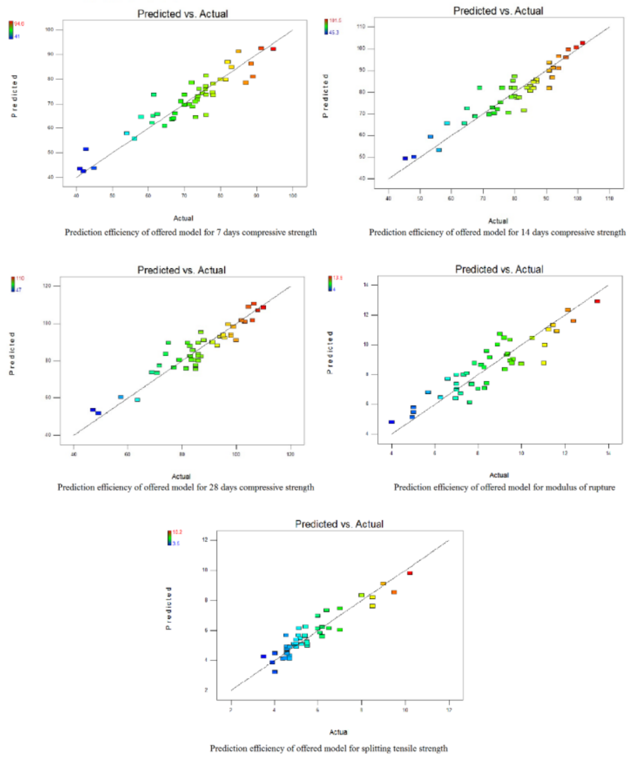

Fig. 2 Prediction efficiency of offered models

level of 5% for 7, 14, and 28 days compressive strengths, moreover, linear A and E are statistically significant factors for all days compressive strength as shown in Table 5. The quadratic A, B, C, D, E are not statistically significant factors at the stipulated level of 5%, however, the quadratic A, B, C, and, E are statistically significant factors at the stipulated level of 5% for 28 days compressive strength. The significance of some two-way interaction terms are given in 7, 14, and 28 days compressive strength in Table 5. A significant two-way interaction explains that the simple effect of a variable is not same at all levels of other variables. The 2-ways interaction of A with B, D, E (AB, AD, AE), B with C and E (BC, BE), and C with D (CD) are statistically significant factors at the stipulated level of 10% for 7 days compressive strength. In 14 days compressive strength, 2-ways interactions of A with B, D (AB, AD), B with D (BD), and C with D (CD) are statistically significant factors at the stipulated level of 10%. Also in 28 days compressive strength, the 2-ways interactions of A with B, D, E, (AB, AD, AE), and B with E (BE) are statistically significant factors at the stipulated level of 10%, those two-way interactions or quadratic variables which we didn't use in the given models were insignificant.

Table 5 Estimated parameters for models at 7, 14, 28 days compressive strength

	Compressive 07 days		Compressive 14 days		Compressive 28 days	
Parameters	Estimate	Prob > f	Estimate	Prob > f	Estimate	Prob > f
Constant	73.55		82.05		89.63	
A	-4.10	0.000183	-4.10	0.000208	-4.19	0.000419
B	0.51	0.600039	0.43	0.662289	0.99	0.358075
C	0.62	0.522755	-0.13	0.89202	-0.37	0.729417
D	-0.41	0.669074	-0.16	0.865862	-1.30	0.229922
E	-11.20	<0.0001	-11.46	<0.0001	-12.00	<0.0001
AB	2.91	0.006164	2.45	0.020269	3.72	0.001868
AD	-1.93	0.060132	-1.78	0.083709	-2.26	0.046967
AE	-1.92	0.061712	-1.42	0.164175	-1.85	0.100197
BC	-1.55	0.127327	-1.43	0.160621	-1.14	0.304248
BE	4.29	0.000154	5.39	0.188816	6.45	<0.0001
CD	-1.68	0.099306	-1.73	<0.0001	----	-----
BD	---	---	1.34	0.093411	-----	-----
A^2	2.04	0.559331	4.86	0.155532	7.85	0.048624
B^2	-3.21	0.361439	-4.24	0.212705	-7.95	0.046197
C^2	---	----	----	----	3.95	0.309034
D^2	-4.36	0.217797	-4.39	0.197407	-8.15	0.041307
E^2	2.09	0.549816	----	----	-----	----

Table 6 Estimated parameter of obtained models for splitting tensile strength and rupture module

	Splitting Tensile strength		Rupture module	
Parameters	Estimate	Prob > f	Estimate	Prob > f
Constant	5.67		8.77	
A	-0.23	0.063382	-0.57	0.002885
B	-0.36	0.004972	-0.58	0.002424
C	0.53	0.000141	0.66	0.000715
D	-0.65	<0.0001	-0.54	0.004209
E	-1.00	<0.0001	-1.71	<0.0001
AB	0.26	0.044944		
AD	-0.13	0.299533	----	-----
AE	----	----	0.24	0.195130
BD	0.14	0.279485		
BE	0.48	0.000508	-----	----
CD	0.12	0.340114	0.42	0.025262
CE	-0.33	0.011287	----	----
DE	0.27	0.035389	-0.25	0.182927
A2	-0.32	0.481555	-0.83	0.197593
B2	-1.17	0.013697	-1.24	0.059639
C2	2.33	0.000014	1.05	0.108133
D2	-0.17	0.711158	0.70	0.274339
E2	-0.56	0.219598	------	-----

Estimated Parameters within probability values for splitting tensile strength and rupture module are given in

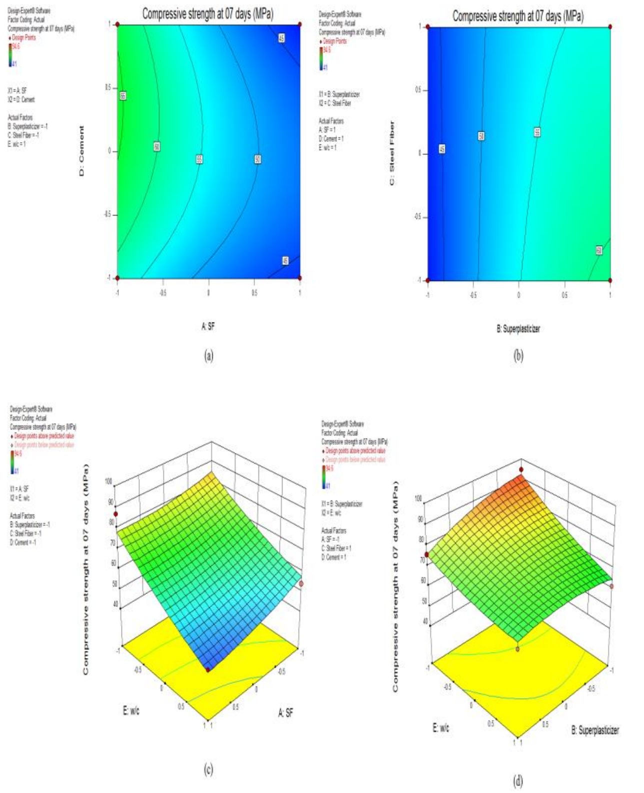

Fig. 3 Contour plot and response surface of 7 days compressive strength

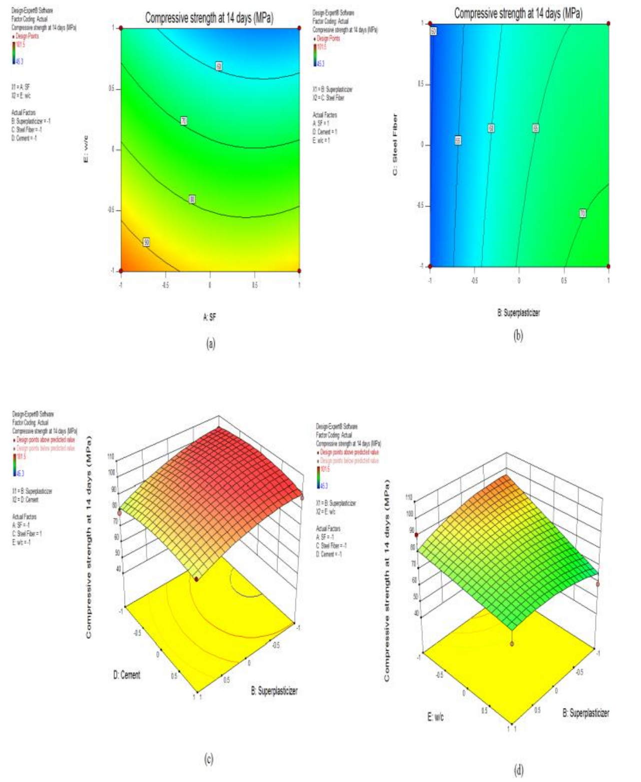

Fig. 4 Contour plot and response surface of 14 days compressive strength

Table 6, it is clear that linear factors A, B, C, D, E are statistically significant factors at the stipulated level of 10% with having probability value of 0.06, 0.005, 0.0001, <0.0001, <0.0001 respectively, for splitting tensile strength and 0.003, 0.002, 0.0007, 0.004, <0.0001, respectively, for rupture module. The quadratic B, C for splitting tensile strength and quadratic B for rupture module are statistically significant factors at the stipulated level of 10%. About 2-ways interactions, as it is given 6, the interaction between A and B (AB), B and E (BE), C and E (CE), and, D with E (DE) are statistically significant factors at the stipulated level of 10% for splitting tensile strength, and interaction between C and D (CD) is statistically significant factor at the stipulated level of 5%.

4. Discussion

The Effects of five concrete mix design parameters (silica fume, superplasticizer, cement, steel fiber, and w/c ratio) on mechanical properties (7, 14, and 28 days compressive strength, splitting tensile strength, and modulus of rupture) have been considered employing response surface methodology. The Effects of variables on responses can be presented graphically by 3D plotting of response value versus variables.

4.1 Effect of parameters on compressive strength

Fig. 3(a) and (b) shows the contours effect of Cement and silica fume amount and also effect of SP amount and steel fibers at fixed variables on 7 days compressive strength, respectively. As it is clearly shown, increasing rate of silica fume from 0.15 to 0.3 of aggregate mass decreases the 7 days compressive strength where amount of SF was changed from 15% to 43% (by weight of cement). Šerelis *et al.* (2015) found that the best ratio for silica fume was 15% (by weight of cement) for UHPC, moreover, Fig. 3(a) shows that the rate of cement was not very significant. So increasing the cement is not effective on 7 days compressive strength as Aldahdooh *et al.* (2013) reported increasing the binder will not enhance the strength because the capillary porosity will increase by increasing the amount of cement. Effect of steel fiber with SF is given in Fig. 3(b) which shows: the effect of steel fiber is negligible for increasing the 7 days compressive strength as Wille *et al.* (2012) found that there is a small improvement in compressive strength by adding fibers.

The combiation effects of SF and w/c ratio is given in Fig. 3(c) Decreasing the w/cratio and amount of silica fume increases the 7 days compresive strength significantly. There is a common belief that decreasing the w/c ratio increases the compressive strength of concrete. The effect of w/c ratio with superplsticizer on 7 days compressive strength are inversely corrolated which is shown in Fig. 3d. The effect of only superplasticizer is not very significant on 7 days compressive strength as shown in the given models but the corrolation between superplasticizer and w/c ratio were found to be very meaningful and effective on 7 days compressive strength.

The contour effect of w/c ratio and amount of silica fume and the contour effect of SP amount and steel fibers at fixed variables on 14 days compressive strength are shown

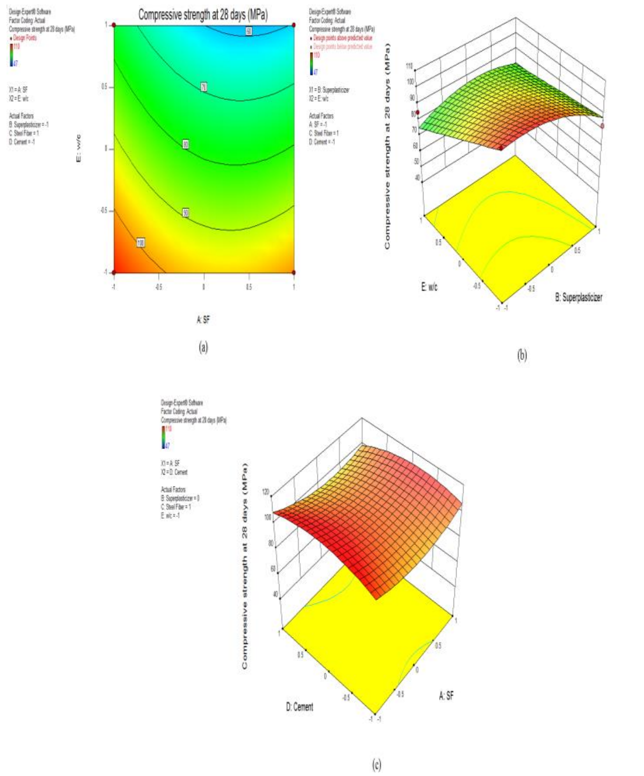

Fig. 5 Contour plot and response surface of 28 days compressive strength

in Fig. 4(a) and (b), respectively. An increase in the amount of silica fume from 0.15 to 0.3 of aggregate mass decreased the 14 days compressive strength where the amount of SF started from 15% to 43% (by the weight of cement) and the 14 days compressive strength was increased by decreasing the w/c ratio which were defined in this study between 0.18 and 0.32 by decreasing the porosity which is shown in Fig. 4(a). Moreover, Fig. 4(b). demonstrates that the rate of steel fiber amount was not very significant on 14 days compressive strength, thus, increasing the fiber content is not effective on the 14 days compressive strength. The model shows that increasing the superplasticizer amount from (0.04 to 0.08 of aggregate mass) has direct effect on 14 days compressive strength.

The response surface of 14 days compressive strength is given in Fig. 4(c) and (d). As shown in Fig. 4(c), the response surface due to cement amount and superplasticizer has increased at low level of superplasticizer amount, and the 14 days compressive strength had negligible increase in the middle level of cement amount as Wang *et al.* (2012) reported. A decrease in superplasticizer and w/c ratio increases the 14 days compressive strength which is given in Fig. 4(d). Dils *et al.* (2012) reported that an increase in the compressive strength is due to reducing the w/c ratio because of the decrease in the capillary pore volume. Adding extra superplasticizer amount can segregate the concrete therefore the strength will be reduced. Thus, in Fig. 4(d), the maximum strength is at low level of w/c ratio and superplasticizer amount.

Fig. 5(a) shows the contour effect of amount of silica fume and w/c ratio on 28 days strength. Therefore, it is clear that decreasing the w/c ratio has a significant effect on

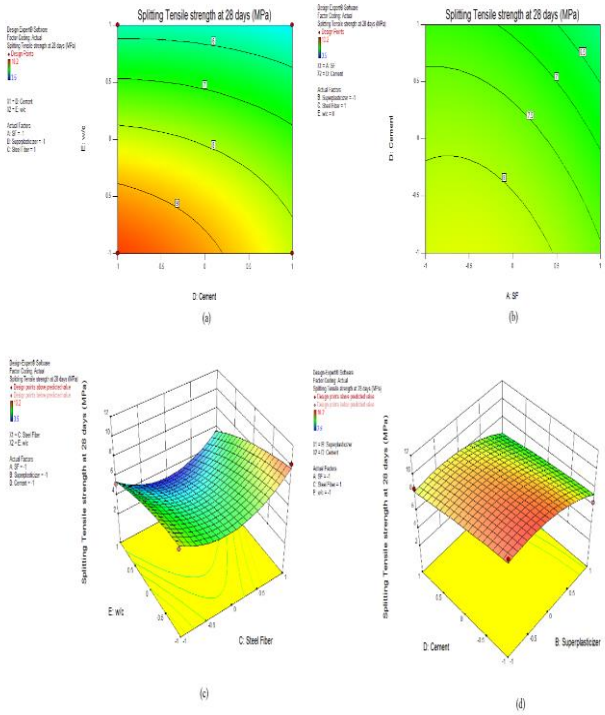

Fig. 6 Contour plot and response surface of splitting tensile at 28 days

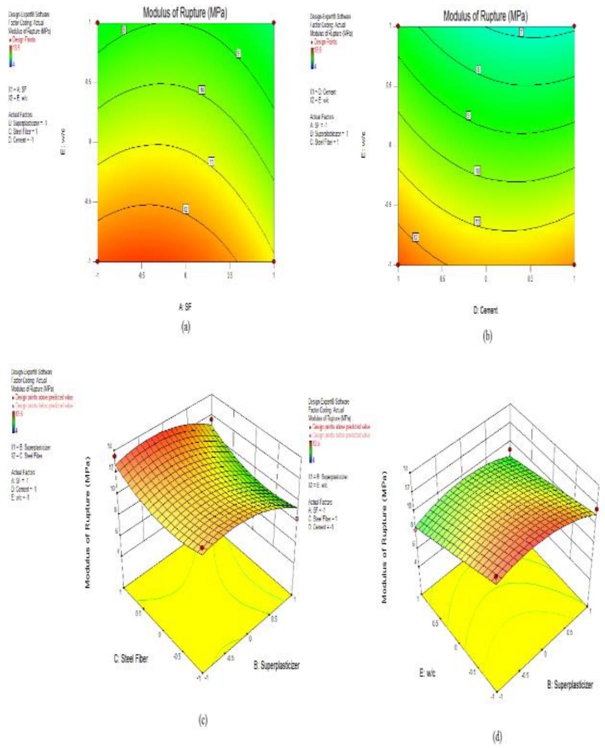

Fig. 7 Contour plot and response surface of modulus of rupture

28 days compressive strength. Silica fume content has inversely affected the 28days compressive strength because by decreasing the amount of silica fume, the 28 days strength is reducing. The corrolation between w/c ratio and SP amount is significant as it is shown in Fig. 5(b). The highest 28 days compressive strength crosses the low level

Table 7 The mix design used for model validity

	Batch 1			Batch 2			Batch 3		
	Code	Factor*	Value (kg)	Code	Factor*	Value(kg)	Code	Factor*	Value(kg)
Sand	---	1.0000	50.000	---	1.0000	50.000	---	1.0000	50.000
Silica Fume	0.50	0.2750	13.750	0.00	0.2500	12.500	-0.50	0.2000	10.000
Super plasticizer	0.50	0.0700	3.500	-1.00	0.0400	2.000	-0.50	0.0500	2.500
Steel Fiber	-1.00	0.1000	5.000	0.25	0.1625	8.125	1.00	0.2000	10.000
Cement	-0.50	0.8500	42.500	0.50	1.1500	57.500	0.00	1.0000	50.000
w/c	-0.50	0.2025	10.125	0.50	0.2725	13.625	-1.00	0.1800	9.000

*In terms of fine aggregate fraction

Table 8 Comparison between actual results and prediction model of responses

	Test 1			Test 2			Test 3		
	Actual (MPa)	Predicted (MPa)	Error (%)	Actual (MPa)	Predicted (MPa)	Error (%)	Actual (MPa)	Predicted (MPa)	Error (%)
7 days Compressive strength (MPa)	70.00	76.63	8.65	62.50	61.65	1.38	87.00	91.655	5.08
14 days Compressive strength (MPa)	78.00	84.79	8.01	66.00	67.21	1.80	94.00	98.67	4.73
28 days Compressive strength (MPa)	93.00	97.85	4.96	72.00	69.22	4.02	103.00	110.6	6.87
Splitting tensile strength (MPa)	7.10	7.36	3.53	4.10	3.87	5.94	10.20	9.54	6.92
Rupture Modulus (MPa)	9.2000	9.47	2.85	7.80	7.38	-5.69	13.5000	12.35	-9.31

SP and w/c ratio. In Fig. 5(c), the interaction between the amount of silica fume and cement is plotted. A decrease in SF Improves the 28 days compressive strength as Ghafari *et al*. (2015) reported in their model. Cement content (0.7 to 1.3 by weight of aggregate) had no effect of Parameters on Tensile strength.

4.2 Effect of parameters on tensile strength

According to Fig. 6(a), decreasing the w/c ratio from 0.32 to 0.18 has significant effect by improving the splitting tensile strength. Kumar and Baskar (2014) modeled the inverse effect of w/c ratio on splitting tensile strength. An amount of cement inversely affected tensile strength by increasing the amount of cement, a decrease was recorded for splitting tensile strength as plotted in Fig. 6(a) and 6(b). By decreasing SF increases the splitting tensile strength as shown in Fig. 6(b).

Fig. 6(c) is showing the interaction of steel fiber (0.1 to 0.2 weight of aggregate) and w/c ratio (0.18 to 0.32). It can be seen that they both have a significant role in splitting tensile strength improvement in the studied range. As Fig. 6(c) shows, that the maximum splitting tensile is created by crossing lowest level of w/c ratio and highest level of steel fiber content. It is a well-known fact that the splitting tensile increases by increasing steel fibers. The interaction of cement amount and superplasticizer is given in Fig. 6(d) and as it shows clearly that by decreasing the cement (0.7 to 1.3 weight of aggregate) and superplasticizer (0.04 to 0.08 weight of aggregate), maximum splitting tensile strength is obtained.

It is clear that w/c ratio is very effective on modulus of rupture of UHPC according to Fig. 7(a) and 7(b). By decreasing the w/c ratio (from 0.32 to 0.18) the modulus of rupture is increasing. Also by decreasing the silica fume amount (from 0.20 to 0.30 by weight of sand), the modulus of rupture increased (Fig. 7(a)). Decreasing the cement content from 1.30 to 0.70 improves the modulus of rupture of UHPC as shown in Fig. 7(b).

The response surface of modulus of rupture between the variables of steel fiber and superplasticizer amount was shown in Fig. 7(c). It is obviously clear that the modulus of rupture increases by increasing steel fiber content from 0.1 to 0.2 (by weight of aggregate) and decreasing the superplasticizer amount from 0.08 to 0.04 (by weight of aggregate). The interaction of superplasticizer and w/c ratio on modulus of rupture was given in Fig. 7(d). It was derived that the interaction of w/c ratio and superplasticizer amount is very significant for modulus of rupture. The lowest level of superplasticizer and the lowest level of w/c ratio gave maximum modulus of which is shown in Fig. 7(d). Thus, by reducing the rate of superplasticizer from 0.08 to 0.04 (by aggregate mass) and decreasing the w/c ratio from 0.32 to 0.18, the modulus of rupture is increased.

5. Models validity

The validity of models were studied by producing 3 randomly mix design batches in terms of code, factor (aggregate unit mass) and the value of produced concrete which is given in Table 7. Then the compressive strength in different days and the splitting tensile strength and modulus of rupture tests (Table 8) were done to check the validity of models. In Table 8, the actual and predicted results were compared and the error for each model was calculated. According to obtained errors the accuracy of the models were verified.

6. Conclusions

The effects of five variables which included amounts of: silica fume, cement, steel fiber, superplasticizer, and w/c ratio on mechanical properties of UHPC with local materials were investigated by using central composition response surface methodology. In this experimental study, interaction and correlation of five variables were analyzed. The validity and significance of models and factors were analyzed by ANOVA. Forty five batches were produced to provide five valid models; 7, 14, and 28-day compressive strength, splitting tensile strength, and modulus of rupture. The most important outcomes of the research are specified below:

Quadratic model with R^2 of 0.87, 0.88, 0.88, 0.88, 0.83 were obtained for 7, 14, and 28 days compressive strength, splitting tensile strength and modulus of rupture tests.

Quadratic models were fitted for 7, 14, and 28 days compressive strength, splitting tensile strength and modulus of rupture responses.

The models were controlled by using actual values and errors of less than 10% for all responses were found.

Increasing the amount of cement paste will not necessarily increase the mechanical properties of UHPC.

The increase in silica fume content (15% to 43% in the cement mass) had negative effect on compressive and tensile strength properties of UHPC.

From the ANOVA statistical modeling, it was found that the interaction of w/c ratio with superplasticizer content was significantly important for improving the mechanical properties such as compressive strength and tensile strength of concrete.

The effect of steel fiber on tensile strength was highlighted but it was negligible for compression property.

References

Aldahdooh, M.A.A., Bunnori, N.M. and Johari, M.M. (2013), "Evaluation of ultra-high-performance-fiber reinforced concrete binder content using the response surface method", *Mater. Des.*, **52**, 957-965.

Alqadi, A.N., Mustapha, K.N.B., Naganathan, S. and Al-Kadi, Q.N. (2013), "Development of self-compacting concrete using contrast constant factorial design", *J. King Saud Univ.-Eng. Sci.*, **25**(2), 105-112.

Bektas, F. and Bektas, B.A. (2014), "Analyzing mix parameters in ASR concrete using response surface methodology", *Constr. Build. Mater.*, **66**, 299-305.

Dils, J., Boel, V. and De Schutter, G. (2013), "Influence of cement type and mixing pressure on air content, rheology and mechanical properties of UHPC", *Constr. Build. Mater.*, **41**, 455-463.

Ghafari, E., Bandarabadi, M., Costa, H. and Júlio, E. (2015), "Prediction of fresh and hardened state properties of UHPC: Comparative study of statistical mixture design and an artificial neural network model", *J. Mater. Civil Eng.*, **27**(11), 04015017.

Lotfy, A., Hossain, K.M. and Lachemi, M. (2015), "Statistical models for the development of optimized furnace slag lightweight aggregate self-consolidating concrete", *Cement Concrete Compos.*, **55**, 169-185.

Mohammed, B.S., Abdullahi, M. and Hoong, C.K. (2014), "Statistical models for concrete containing wood chipping as partial replacement to fine aggregate", *Constr. Build. Mater.*, **55**, 13-19.

Mosaberpanah, M.A. and Eren, O. (2016), "CO_2-full factorial optimization of an ultra-high performance concrete mix design", *Eur. J. Environ. Civil Eng.*, 1-14.

Mosaberpanah, M.A. and Eren, O. (2016), "Statistical flexural toughness modeling of ultra high performance concrete using response surface method", *Comput. Concrete*, **17**(4), 477-488.

Rahdar, H.A. and Ghalehnovi, M. (2016), "Post-cracking behavior of UHPC on the concrete members reinforced by steel rebar", *Comput. Concrete*, **18**(1), 139-154.

Sebaibi, N., Benzerzour, M., Sebaibi, Y. and Abriak, N.E. (2013), "Composition of self-compacting concrete (SCC) using the compressible packing model, the Chinese method and the European standard", *Constr. Build. Mater.*, **43**, 382-388.

Senthil Kumar, K. and Baskar, K. (2014), "Response surfaces for fresh and hardened properties of concrete with E-waste (HIPS)", *J. Waste Manage*.

Šerelis, E., Deligia, M., Vaitkevičius, V. and Kerševičius, V. (2015), "Influence of water to cement ratio with different amount of binder on properties of ultra-high performance concrete", *J. Sustain. Architect. Civil Eng.*, **10**(1), 78-86.

Wang, C., Yang, C., Liu, F., Wan, C. and Pu, X. (2012), "Preparation of ultra-high performance concrete with common technology and materials", *Cement Concrete Compos.*, **34**(4), 538-544.

Wang, X.Y. (2014), "Properties prediction of ultra high performance concrete using blended cement hydration model", *Constr. Build. Mater.*, **64**, 1-10.

Wille, K., Naaman, A.E., El-Tawil, S. and Parra-Montesinos, G.J. (2012), "Ultra-high performance concrete and fiber reinforced concrete: Achieving strength and ductility without heat curing", *Mater. Struct.*, **45**(3), 309-324.

Yu, R., Spiesz, P. and Brouwers, H.J.H. (2014), "Mix design and properties assessment of ultra-high performance fibre reinforced concrete (UHPFRC)", *Cement Concrete Res.*, **56**, 29-39.

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