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Uses of Central Composite Design and Surface Response to Evaluate the Influence of Constituent Materials on Fresh and Hardened Properties of Self-Compacting Concrete

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Abstract

This research presents the details of an investigation carried out to study the effect of the addition of constituent material parameters on the fresh and hardened state properties of self-compacting concrete using a central composite design approach combined with response surface methodology. Self-Compacting Concrete (SCC) mixtures were made with the addition cement, coarse aggregate, sand, fly ash and super plasticizer in various proportions and their fresh state properties (J-ring, segregation resistance and V-funnel) and hardened properties (compressive strength at 28 days and modulus of elasticity) were measured. Results were analysed using a statistical model that was able to predict the effect of the independent variables on the responses by using multiple regression analysis. The coupled effect of the responses was carried out. An analysis of variance was used to determine the adequacy between the model and experimental values. It was concluded that models of a full quadratic can be used to evaluate the influence of constituent materials on the properties of SCC. All the mixtures developed exhibited fresh state property values which were within the range permitted in the SCC guidelines. Optimizations of the responses were done by using response surface methodology. It was concluded that the fresh properties cited were 18.3 seconds V-funnel, 849 mm J-ring flow, and 17.8% segregation resistance and the hardened properties were 35.254 to 48.174 MPa of the compressive strength and 27.214 to 39.026 MPa for the modulus of elasticity.

Keywords: *central composite design, self-compacting concrete, compressive strength, modulus of elasticity*

1. Introduction

The construction industry is witnessing rapidgrowth around the world and the use of concrete in construction has become pervasive. Buildings, in recent years, have increased in height, and high-strength concrete with good fresh properties is now used in construction of high rise buildings, nuclear power plants, and submarine works instead of normal concrete in order to enhance the life and durability of the structures. Self-Compacting Concrete (SCC) is categorized as a high performance concrete by its capability to spread into place under its own weight without the need for vibration, and its capability to avoid segregation and blocking. The advantages of SCC are increased durability, reduced onsite labour requirement and increased quality. Many researchers have investigated the use of SCC in composite materials, as a self-flowing concrete in building constructions using different theoretical, empirical and computer simulation approaches.

Response Surface Methodology (RSM) is a tool of modern statistics, is used to study the relationship between multiple responses and a number of parameters. It can be used to investigate the relative significance of multi variables in any complex form of interaction (Mantogary, 2001).

High Strength Concrete (HSC) mixes are generally characterized by low water to binder ratio, high consumption of cement, and the presence of chemicals and fillers (Mehta and Aitcin, 1990). Okamura and Quchi (1999) identified that SCC is a concrete that is able to flow in the interior of the formwork, filling it in a natural manner and passing through the reinforcing bars and other obstacles, flowing and consolidating under the action of its own weight. Prasad *et al*. (2008) recognized that SCC is a new kind of High Performance Concrete (HPC) with excellent deformability and segregation resistance. Phan *et al*.

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(2006) declared that SCC is characterized by the high fluidity under its own weight such that it can be placed without vibration, easily fill the small interstices of formwork and be pumped over long distances. Khayat *et al.* (1999) reported that SCC is a highly flowable, yet stable concrete that can spread into place and fill the formwork without any consolidation and without undergoing significant separation. Ferraris *et al*. (1999) defined SCC as a form of concrete that is able to flow under its own weight and completely fills the formwork even in the presence of dense reinforcement, without the need of any vibration whilst at the same time maintain homogeneity. Al Qadi *et al.* (2009) used a central composite design methods to model the influence of key mixtures included slump flow, L-Box and sieve analysis.

Khatib (2008) studied the effects of the properties of SCC by substituting the cement content from 0 to 80% with fly-ash. His research focused on the fresh, hardened and durability properties of SCC and he conducted experiments on slump flow, compressive strength, ultrasonic velocity, absorption and shrinkage. In each test the water/binder ratio was fixed at 0.36 for all mixes. It was concluded that by increasing the fly ash content up to 40% the strength and absorption will increase and so the shrinkage will decrease, while absorption increased from 1 to 2%. A direct relationship between fly ash and shrinkage time was noted. Mehta and Monteiro (1993) stated that the static modulus of elasticity of a material under tension or compression is given by the slope of the stress (σ) – strain (ε) curve under uniaxial loading. Vengala *et al.* (2003) found that the use of fine fly ash for obtaining self compacting concrete resulted in an increase in the 28 day compressive strength by about 38%. Self compacting ability was achieved when volume of paste was ranged between 0.43 and 0.45 of the studied fraction volume.

Al Qadi *et al.* (2009) used statistical modelling to model the influence of key mixture parameters (cement, water to powder ratio, fly ash and super plasticizer) on the hardened properties affecting the performance of SCC. The models were valid for a wide range of mixture proportioning. The derived numerical models could be useful to reduce the test procedures and number of trials of mix proportioning of SCC. The researchers concluded that full quadratic models in all the responses showed the best models. Demir (2009) ascertained the mechanical properties of waste block granites to be used in concrete production. The aggregates were tested in terms of density and water absorption. Tests for compressive strength, splitting tensile strength, and the static modulus of elasticity were carried out on the hardened concrete. The result of the study results showed that the mechanical properties of concrete specimens were confirmed to meet the Turkish and European concrete production standards.

Subai (2009) studied the effect of class C fly ash on the mechanical properties of cement by using artificial neural network and regression methods. Tests on unit weight, flexural tensile strength and compressive strength tests were performed after two, seven and the 28 days. Two different estimation model Regression Techniques (RT) and an Artificial Neural Network (ANN) method were used to determine the flexural tensile strength and the compressive strength of the cement specimens**.**

Results were determined for the compressive and flexural tensile strength values of mortars containing various amounts of class C fly ash and it was concluded that strength could be predicted in a quite short period of time with tiny error rates by using the multilayer feed-forward neural network models rather than regression techniques.

Ogluta and Serin (2010) used the Toguchi experiment design technique for evaluation by Analysis of Variance (ANOVA) and single noise ratio. The L_9 orthogonal design was performed in nine experiments. Optimum conditions for maximizing the strength of the fabric experiment were processed easily by the Taguchi method. Bartos *et al.* (2008) defined the key properties that can make fresh self-compacting concrete and outlined test methods for its assessment. Also stages were studied from the construction process of materials selected to design and mixing, transporting, placing and finishing of SCC.

This current research describes and provides a guideline on the procedure for mix proportions of SCC. Experimental design, response surface methodology, contours, and surface response were used for model prediction and optimization of responses of the SCC parameters. The significance of this research is focusing on constituent materials and their corresponding proportions in SCC. Furthermore, there is still a lack of standardization in SCC mixes. So this requires finding additional methods such as central composite design and response surface methodology to handle and reduce the cost, time, and number of experimental trials of SCC.

2. Materials and Methods

2.1 Materials

Ordinary Portland cement as available in the local market was used in the investigation. The Cement used was tested for various proportions as per (ASTM C150-85A, 2006) the specific gravity was 3.15 and Blaine fineness was 2910 cm^2/g. Crushed angular granite material of 20 mm nominal size obtained from a local source was used as coarse aggregate. The specific gravity was 2.45, the absorption value was 1.5%., fineness modulus of 6.1 and with a bulk density of 1480 kg/m^3 which conforms to (ASTM C 33-86, 2006) was used. The fine aggregate consisted of river sand with a nominal size of 4.75 mm, with a modulus of fineness of 2 to 3.

The specific gravity was 2.6, and the absorption value was 6.4%. Fly Ash (FA) obtained from the Kapar Thermal Power Station, Selangor, Malaysia, was used in the investigation.The fly ash was tested for its pozzolanicity according to (ASTM C 618, 2006) and found to be type-II Class F which can beused directly without any modification of properties.The specific gravity of the fly ash was 2.32, and the Blaine fineness was 2423 cm^2/g. Superplasticizer (SP): A Polycarboxylicether (PCE) based Superplasticizer (SP) was used in the investigation. The superplasticizer conforms to (ASTM C 494-92, 2006) with a specific gravity of 1.15 with type A and type F being in an aqueous form and both were free flowing liquid type superplasticizer. Potable water conforming to (ASTM D 1129, 2006) was used for mixing and curing.

2.2 Methods

Many researchers have used Design of Experiment (DOE) technique to evaluate mix-proportioning. The central composite design method has been chosen to be employed to limit the number of experimental runs compared to factorial design. This would enable modelling of the mixture proportions involving interaction and quadratic terms. These models were used for optimization of the SCC mixes.In a four factors experiment, the central composite design is composed of four components, the factorial portion (2^4) =16, the axial (star) portion (2×4) = 8.A statistical experimental design (four factors at two levels) response surface consisting of 4 factors and 31 points (16 factorial points, 8 axial points, and 7 central points) was used to evaluate the influence of two different levels for each variable on the relevant concrete properties.

Such a two-level factorial design requires a minimum number of tests for each variable (Montgomery, 1996). The fact that the expected responses do not vary in a linear manner with the selected variable and to enable the quantification of the prediction of the responses, a central composite plan was selected, where the response could be modelled in a quadratic manner. Since the error in predicting the responses increases with the distance from the centre of the modelled region, it is advisable to limit the use of the models to an area bound by coded values corresponding to lower $-\alpha$ to the upper $+\alpha$ limits.

The parameters were carefully selected to carry out composite factorial design, where the effect of each factor was evaluated at five different levels, in codified values of $-\alpha$, -1, 0, + 1, $+\alpha$. Each value was chosen so that the variance of the response predicted by the model would depend only on the distance from the centre of the modelled region. The value of α is equal to $N_f^{1/4}$ where N_f is the number of factorial points $2^4 = 16$ then $\alpha = 16^{1/4} = 2$. Seven (7) replicate central points were prepared to estimate the degree of experimental error for the modelled responses. Appropriate commercial software was used for the statistical analysis of the results. Four key parameters that can have significant influence on the mix characteristics of SCC were selected to derive the mathematical models for evaluating relevant properties. The SCC responses modelled were on fresh properties for filling ability, passing ability, and stability (V-funnel time, J-ring flow, segregation resistance) and hardened properties (28 days compressive strengths and modulus of elasticity). Table 2 shows the experimental design runs.

3. Mixture Proportioning

All concrete mixes were prepared in 40-Litre batches in a rotating planetary mixer. The batching sequence consisted of homogenizing the sand and coarse aggregate for 30 seconds, then adding about half of the mixing water into the mixer and continue to mix for one more minute. The mixer was covered with a plastic cover to minimize the evaporation of the mixing water and to let the dry aggregates in the mixer absorb the water. After 5 minutes, the cement and fly ash were added and mixed for another minute. Finally, the SP and the remaining water were introduced, and the concrete mixed for a further 3 minutes.

Thirty one mixes were investigated for the fresh properties by V-funnel, J-ring, and segregation resistance to handle its fresh properties. Ninety nine cubes (100×100×100 mm) were cast and kept moist under wet conditions for each mix to determine compressive strength after 28 days. For the modulus of elasticity, ninety nine cylinders (150×300 mm) were cast and tested after 28 days, also the average of three specimens were measured for each test. Table 3 shows the data for mix proportion parameters and the responses of fresh and hardened properties.

4. Development of Statistical Models

Statistical experimental design of four factors at two levels was used to evaluate the influence of two different levels for each variable of the relevant SCC properties. Such a two-level factorial design requires a minimum number of tests for each variable (Montgomery, 1996). The fact that the expected responses do not vary in a linear manner with the selected variable and to enable the quantification of the prediction of the responses, a central composite plan was selected, where the response could be modelled in a linear, interaction, full and pure quadratic manner. Since the error in predicting the responses increases with the distance from the centre of the modelled region, it is advisable to limit the use of the models to an area bound by values corresponding to $-\alpha$ to $+\alpha$ limits.

The parameters were carefully selected to carry out central composite design, where the effect of each factor was evaluated at five different levels, in codified values of $-\alpha$, -1, 0, 1, $+\alpha$. The value of the α value was chosen so that the variance of the response predicted by the model would depend only on the distance from the centre of the modelled region.

The value of α value is taken here as ± 2. Seven replicate central points were prepared to estimate the degree of experimental error for the modelled responses. Appropriate Minitab software was used for the statistical analysis of the results.

Four key parameters that have a significant influence on the mix characteristics of SCC were selected to derive the mathematical models for evaluating relevant properties. The experimental levels of the variables (maximum and minimum), boundary of cement content, w/p, fly ash content, SP dosage were defined. The modelled experimental region consisted of mixes ranging between the coded variables of -2 to +2 as given in Table 1. The derived statistical models are valid for mixes with w/p ranging from 0.3 to 0.38 by mass, dosages of SP ranging from 7.2 to 10.8 kg/m^3 1.8% of total powder content (by mass) (Su *et al.*, 2001), cement content ranging from 400 to 450 kg/m^3 and fly ash content ranging from 110 to 150 kg/m^3. The mass of coarse aggregate was 25% to 35% by volume of the mix. The SCC responses modelled were compressive strengths at 28-days. The moduli of elasticity models are given in Eqs. (1), (2), (3), and (4).

Linear model:

$$Y = b_o + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4 \qquad (1)$$

where Y = response, X = factors, b_o, b_1, b_3, and b_4= regression coefficients.

Interaction model:

$$Y = b_o + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4 + b_{12}X_{12} + b_{13}X_{13} + b_{14}X_{14} + b_{23}X_{23} + b_{24}X_{24} + b_{34}X_{34} \qquad (2)$$

This is a linear model plus interaction with b_{12}= interaction regression coefficient of b_1 on b_2 and also for the other coefficients, while $X_{12}, ..., X_{14}, X_{23}, X_{24}$, and X_{34} = effect of factor X_1 on X_2, X_3, X_4 and the effect of factor X_2 on X_3 and X_4, and the effect of factor X_3 on X_4. If there is curvature in the data, then a polynomial model of higher degree is used. The second order model which includes all interaction terms, was used to calculate the predicted response.

Full quadratic:

$$Y = b_o + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4 + b_{12}X_{12} + b_{13}X_{13} + b_{14}X_{14} + b_{23}X_{23} + b_{24}X_{24} + b_{34}X_{34} + b_{11}X_{11}^2 + b_{22}X_{22}^2 + b_{33}X_{33}^2 + b_{44}X_{44}^2 \qquad (3)$$

where b_{11}, b_{22}, b_{33}, and b_{44} = the square of each of the regression coefficients b_1b_1, also second order of $X_1X_1 = X_{11}^2$ and the other terms follow the same procedure.

Pure quadratic:

$$Y = b_o + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4 + b_{11}X_{11}^2 + b_{22}X_{22}^2 + b_{33}X_{33}^2 + b_{44}X_{44}^2 \qquad (4)$$

where Y represents a V-funnel, J-ring and SR, compressive strength, and modulus of elasticity for each of the four models and the coefficient of the response surface equation were determined by using Minitab software (Box and Draper, 1987; Khuri and Cornell, 1987; Montgomery, 2001).

5. Results and Discussion

The study was carried out according to a central composite design and points were measured according to the design as shown in Table 2. A polynomial equation was used to express the responses as a function of the independent variables of the four parameters in Eqs. (1), (2), (3) and (4).

Statistical models of linear, interaction, full quadratic and pure quadratic were measured on the fresh and hardened properties of SCC.

Contour and response surface plots are useful for establishing the desirable response values and operating conditions. In a contour plot, the response surface is viewed in a two dimensional plane with all the points of the same level connected to form contour lines of constant response. Alternatively, a surface plot displays three dimensional views that gave a clearer picture of the response surface. The illustrations in Figs. 1 to 5 demonstrate these types of plots.

Table 1. Value of Coded Variables

Coded values	-2	-1	0	1	2
Cement (kg/m^3)	400	412.5	425	437.5	450
W/P ratio	0.3	0.32	0.34	0.36	0.38
FA (kg/m^3)	110	120	130	140	150
SP (kg/m^3)	7.2	8.1	9	9.9	10.8

Table 2. Experimental Design Runs

RunOrder	Blocks	Cement X_1	W/P X_2	FA X_3	SP X_4
1	1	0	2	0	0
2	1	0	0	0	2
3	1	0	0	2	0
4	1	0	0	0	0
5	1	0	0	0	0
6	1	0	0	0	0
7	1	0	0	0	0
8	1	-1	1	-1	1
9	1	0	0	0	0
10	1	1	1	1	-1
11	1	-1	-1	-1	1
12	1	1	-1	-1	1
13	1	0	0	0	0
14	1	2	0	0	0
15	1	-1	1	1	1
16	1	0	0	0	0
17	1	1	1	-1	-1
18	1	0	0	0	-2
19	1	1	-1	1	-1
20	1	-1	1	-1	-1
21	1	1	1	-1	1
22	1	0	0	-2	0
23	1	-1	-1	-1	-1
24	1	0	-2	0	0
25	1	-2	0	0	0
26	1	-1	1	1	-1
27	1	-1	-1	1	1
28	1	1	1	1	1
29	1	1	-1	-1	-1
30	1	-1	-1	1	-1
31	1	1	-1	1	1

5.1 Fresh Properties of SCC

The effects of the cement, water to powder ratio, fly ash and superplasticizers on the fresh properties of SCC (filling ability, passing ability and stability) were investigated by the response surface methodology. The level of independent parameters in Table 1 was shown to determine the basis of the preliminary

Table 3. Mix Proportions of All Mixes used in the Central Composite Design and Responses of Fresh and Hardened Properties of SCC

Mix No.	Cement (kg/m^3)	W/P ratio	FA (kg/m^3)	SP (kg/m^3)	Sand (kg/m^3)	CA (kg/m^3)	V-Funnel (seconds)	J-Ring (mm)	SR (%)	f_{c28} (MPa)	E (GPa)
	X_1	X_2	X_3	X_4	X_5	X_6	Y_1	Y_2	Y_3	Y_4	Y_5
1	450.0	0.340	130	9.0	869	700	6.00	880.0	19.00	35.254	34.000
2	425.0	0.340	130	10.8	889	716	6.00	870.0	17.00	45.000	32.862
3	425.0	0.340	110	9.0	913	735	14.00	800.0	18.00	36.235	31.950
4	425.0	0.340	130	7.2	894	720	10.35	880.0	16.00	46.484	34.926
5	412.5	0.360	140	9.9	876	705	3.88	878.0	22.00	42.000	36.000
6	425.0	0.300	130	9.0	922	742	20.00	750.0	17.00	45.216	36.000
7	425.0	0.380	130	9.0	861	693	19.00	875.0	19.00	47.000	34.300
8	412.5	0.360	140	8.1	878	707	19.83	828.0	16.00	44.543	32.752
9	412.5	0.320	140	9.9	906	729	17.00	840.0	18.00	45.102	32.750
10	412.5	0.360	120	9.9	898	723	17.00	815.0	19.00	48.174	32.096
11	412.5	0.320	140	8.1	909	731	14.00	690.0	12.00	47.181	28.886
12	437.5	0.360	120	8.1	877	706	6.00	738.0	7.30	41.927	32.320
13	437.5	0.360	140	9.9	853	686	8.00	820.0	18.00	39.152	33.798
14	450.0	0.340	130	9.0	869	700	7.80	663.5	6.00	45.997	30.589
15	437.5	0.320	140	9.9	884	712	8.00	812.0	10.00	41.000	31.576
16	425.0	0.340	130	9.0	892	718	7.32	825.0	18.00	40.747	36.931
17	412.5	0.320	120	9.9	927	746	10.50	760.0	12.20	38.587	34.138
18	412.5	0.360	120	8.1	900	725	8.25	732.5	12.40	44.732	31.830
19	412.5	0.320	120	8.1	929	748	17.00	816.5	16.00	43.337	32.540
20	437.5	0.320	140	8.1	887	714	3.78	848.5	16.30	37.051	39.026
21	437.5	0.320	120	9.9	905	728	4.79	858.0	18.00	41.055	30.742
22	437.5	0.360	120	9.9	874	704	8.00	740.0	10.00	42.657	34.345
23	437.5	0.320	120	8.1	907	730	9.50	792.5	9.00	42.433	29.284
24	437.5	0.360	140	8.1	855	688	9.22	777.5	17.20	43.000	31.288
25	400.0	0.340	130	9.0	914	736	20.00	874.0	16.00	46.833	36.234
26	425.0	0.340	130	9.0	892	718	18.00	850.0	17.00	47.752	34.789
27	412.5	0.360	120	9.9	898	723	17.00	860.0	23.00	46.200	33.716
28	412.5	0.320	140	8.1	909	731	6.80	764.5	16.40	41.056	27.214
29	425.0	0.380	130	9.0	861	693	15.00	600.0	0.11	41.451	29.815
30	437.5	0.320	120	9.9	905	728	15.68	662.5	1.00	38.457	31.250
31	425.0	0.340	150	9.0	870	701	9.81	719.0	7.40	38.000	35.995

Table 4. Regression Coefficients, T-Values, and P-Values for Fresh Properties of SCC

Variable	V-funnel values			J-ring values			Segregation resistance values		
	Coef.	T-value	P-value	Coef.	T-value	P-value	Coef.	T-value	P-value
Constant	-3064.11	-4.280	0.001	-40980.2	-4.014	0.001	-4498.11	-4.932	0.000
C	11.32	4.517	0.000	89.3	2.498	0.024	10.54	3.301	0.005
w/p	2507.6	1.972	0.066	68268.9	3.766	0.002	5340.22	3.298	0.005
FA	2.14	0.872	0.396	114.0	3.262	0.005	14.92	4.782	0.000
Sp	33.10	1.244	0.231	639.3	1.685	0.111	75.26	2.220	0.041
C*w/p	3.27	1.462	0.163	-4.9	-0.153	0.880	-0.67	-0.236	0.816
C*FA	0.01	1.693	0.110	-0.0	-0.263	0.796	-0.01	-2.327	0.033
C*Sp	0.00	0.093	0.927	1.2	1.660	0.116	-0.02	-0.342	0.737
w/p*FA	-3.25	-1.163	0.262	-172.7	-4.336	0.001	-19.90	-5.595	0.000
w/p*Sp	118.16	3.808	0.002	-2081.6	-4.705	0.000	-77.40	-1.958	0.068
FA*Sp	-0.16	-2.631	0.018	0.3	0.381	0.709	-0.06	-0.816	0.426
C*C	-0.02	-5.976	0.000	-0.1	-2.896	0.011	-0.01	-2.867	0.011
w/p*w/p	-6807.92	-6.518	0.000	-33443.1	-2.245	0.039	-2376.60	-1.786	0.093
FA*FA	-0.01	-2.479	0.025	-0.2	-3.190	0.006	-0.01	-1.270	0.222
Sp*Sp	-3.01	-5.830	0.000	-26.2	-3.567	0.003	-1.73	-2.632	0.018

Table 5. Regression Coefficients, T-Values, and P-Values for Hardened Properties of SCC

Variable	Compressive strength values			Modulus of elasticity values		
	Coef.	T-value	P-value	Coef.	T-value	P-value
Constant	-2410.29	-5.395	0.000	-251.46	-0.520	0.610
C	7.41	4.735	0.000	-1.11	-0.655	0.522
w/p	3341.92	4.212	0.001	1662.81	1.936	0.071
FA	3.84	2.511	0.023	4.11	2.482	0.025
Sp	10.51	0.633	0.536	-4.20	-0.234	0.818
C*w/p	-2.26	-1.618	0.125	-1.50	-0.992	0.336
C*FA	-0.01	-2.485	0.024	-0.01	-1.753	0.099
C*Sp	-0.03	-1.009	0.328	0.12	3.620	0.002
w/p*FA	-0.30	-0.171	0.866	-5.26	-2.786	0.013
w/p*Sp	35.57	1.837	0.085	-62.64	-2.988	0.009
FA*Sp	0.08	2.106	0.051	0.02	0.526	0.606
C*C	-0.01	-3.772	0.002	0.00	0.756	0.460
w/p*w/p	-4048.90	-6.211	0.000	373.69	0.530	0.604
FA*FA	-0.01	-1.969	0.067	-0.00	-0.405	0.691
Sp*Sp	-1.14	-3.537	0.003	-1.64	-4.717	0.000

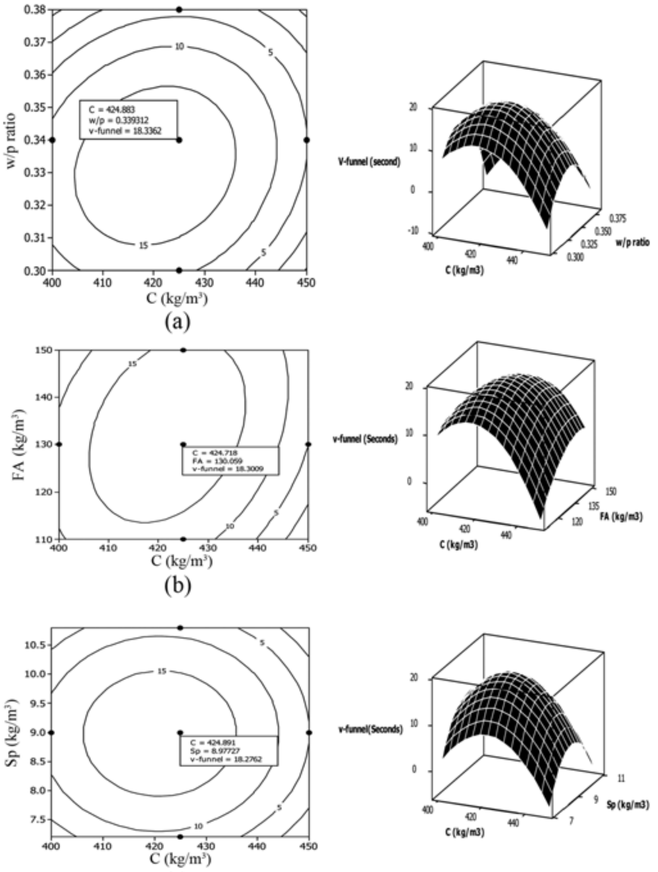
Table 6. Summary of Fresh and Hardened Properties for Full Quadratic Models of SCC

Model	R^2 (%)	R^2_{adj} (%)	F-value	P-value	SSE	Regression Equation
V-funnel(s)	90.5	82.3	10.93	0.000	79.87	V-Funnel (Sec.) = - 3064.11 + 11.32C + 2507.63 w/p + 2.14FA + 33.1SP + 3.27 C*w/p + 0.01 C*FA - 3.25 w/p*FA + 118.16 w/p*SP - 0.16 FA*SP - 0.02 C*C - 6807.92 w/p*w/p - 0.01FA*FA - 3.01SP*SP
J-ring (mm)	90.1	81.4	10.39	0.000	16239	J-Ring (mm) = - 40980.2 + 89.3C + 68268.9 w/p + 114.0 FA + 639.3 SP - 4.9 C*w/p + 1.2C*SP - 172.7 w/p*FA - 2081.6 w/p*SP + 0.3F A*SP - 0.1 C*C - 33443.1 w/p*w/p - 0.2 FA*FA - 26.2 SP*SP
SR(%)	86.2	74.2	7.17	0.000	129.58	Segregation Resistance (%) = - 4498.11 + 10.54 C + 5340.22 w/p + 14.92 FA + 75.26 SP - 0.67 C*w/p - 0.01 C*FA - 0.02 C*SP 19.90 w/p*FA - 77.40 w/p*SP - 0.06 FA*SP - 0.01 C*C - 2376.60 w/p*w/p - 0.01 FA*FA - 1.73 SP*SP
fC28 (Mpa)	92.0	85.0	13.10	0.000	31.11	f_{c28} (MPa) = - 2410.29 + 7.41C + 3341.92 w/p + 3.84 FA + 10.51 SP - 2.26 C*w/p - 0.01 C*FA - 0.03 C*SP - 0.30 w/p*FA + 35.57 w/p*SP + 0.08 FA*SP - 0.01 C*C - 4048.90 w/p*w/p - 0.01 FA*FA - 1.14 SP*SP
E(Gpa)	81.8	65.9	5.14	0.001	36.45	E (GPa) = - 251.46 - 1.11C + 1662.81 w/p + 4.11 FA - 4.20 SP - 1.50C*w/p - 0.01 C*FA + 0.12 C*SP - 5.26 w/p*FA 62.64 w/p*SP + 0.02 FA*SP + 373.69 w/p*w/p - 1.64 SP*SP

experiments as reported in Table 3. The experimental values for filling ability, passing ability and stability under different treatment conditions are presented in Table 4 and Table 5 show that the significance of each factor for a given response is measuring using a t-test values Student's distribution. The measurement of significant evidence that the factors are not equal to zero is often based on a probability less than 0.05.

The P-values for fresh properties of SCC for the second order polynomial equations were measured. The contribution of the proposed factor had a highly significant influence on the measured response. The design models are summarized in Table 6. The result of the derived models was prepared with the correlation of coefficients and the relative significance. The estimates of factors were referred to the coefficients of the model found by least square methods. The R^2 values of the response surface models for the V-funnel time, J-ring flow, and segregation resistance were 90.5, 90.1, and 86.2% for the full quadratic equation. The high correlation coefficient of the dependent variable (response) shows a good correlation that considered at least 95% of the measured values and thus can be applied for the predicted models.

Figure 1 shows the response surface and contour plot versus v-funnel as (a) function of cement (C) and w/p, (b) a function of C and fly ash and, (c) a function of C and SP of SCC. These plots are useful for the optimization of responses and visualizing the results of the parameters to make the statistical model easier for analysis. Fig. 1(a) shows the relation between cement content and w/p ratio and it indicates that the optimum of 18.33 seconds

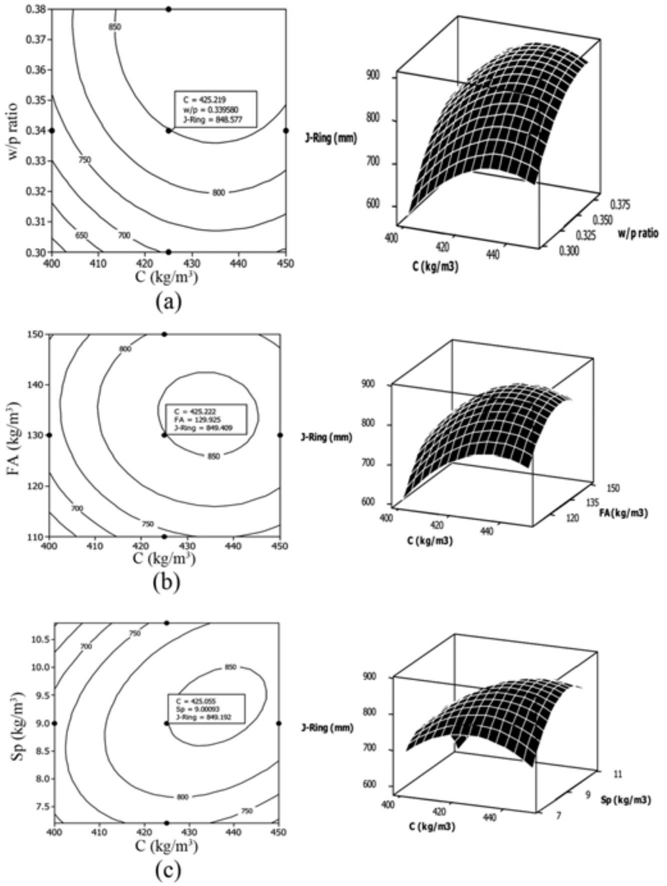


(a)

(b)

(c)

Fig. 1. Response Surface and Contour Plot vs V-Funnel for: (a) Function of Cement and w/p, (b) Function of Cement and Fly Ash, and (c) Function of Cement and SP of SCC



(a)

(b)

(c)

Fig. 2. Response Surface and Contour Plot vs J-Ring for: (a) Function of Cement and w/p, (b) Function of Cement and Fly Ash, and (c) Function of Cement and SP of SCC

V-funnel was seen at a 424.547 kg/m^3 cement content, and 0.34w/p when other parameters are fixed. Also, Fig. 1(b) shows the relationship between cement content and fly ash content. The optimum of 18.3 seconds V-funnel was cited at 424.718 kg/m^3 cement content and 129.925 kg/m^3 fly ash content. Lastly, in Fig. 1(c) the relationship between cement content and dosages of superplasticizer indicate that the optimum of 18.28 seconds V-funnel was measured at 424.891 kg/m^3 cement content and 8.977 kg/m^3 super plasticizer.

Figure 2 shows the response surface and Contour plot versus J-ring for (a) a function of cement and w/p (b) a function of cement and fly ash and, (c) a function of cement and SP of SCC. Fig. 2(a) shows the relation between cement content and w/p ratio. It indicates that the optimum of 849.19 mm J-ring was seen at 425.219 kg/m^3 cement content, and 0.34 w/p when the other parameters are fixed. Furthermore, Fig. 2(b) shows the relationship between cement content and fly ash content. The optimum of 849.409 mm J-ring was cited at 425.222 kg/m^3 cement content and 129.925 kg/m^3 fly ash content. Lastly, in Fig. 2(c) the relationship between cement content and dosages of superplasticizer indicate that the optimum of 849.192 mm J-ring was measured at 425.055 kg/m^3 cement content and 9.00 kg/m^{3}superplasticizer.

In Figs. 3(a), (b), and (c) the graphs show the contour plots obtained from the calculated response surface plots. The fitted surface has a maximum point which is cement of 425 kg/m^3 at 0.34 w/p and fly ash of 130 kg/m^3 and SP of 9 kg/m^3. Fig. 3(a), shows the variation of segregation resistance with cement content and water to powder ratio. This graph shows that as the cement content increases the segregation resistance increases slightly, while by increases the water to powder ratio the segregation increases sharply

In addition, Fig. 3(b) shows the variation of segregation resistance with cement content and fly ash content. This graph shows that as the cement content increases the segregation increases. The surface of the curve concave down with a maximum value at the midpoint, which was indicated for 130 kg/m^3 fly ash. Furthermore, Fig. 3(c) gives the response surface plots for the variation of segregation resistance with cement content superplasticizer. As cement, content increases the segregation resistance increases, while the concave of the surface down with maximum midpoint super-plasticizer occurs at 9 kg/m^3. Hence it is concluded that segregation resistance increases with an increase in cement content.

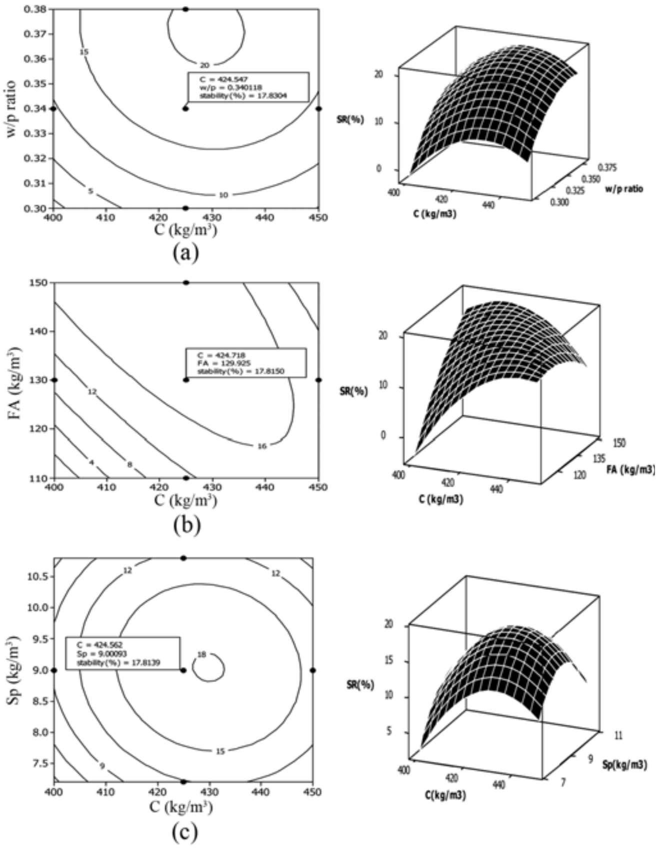


Fig. 3. Response Surface and Contour Plot vs. Segregation Resistance: (a) Function of Cement (C) and w/p, (b) Function of C and Fly Ash, and (c) Function of C and SP of SCC

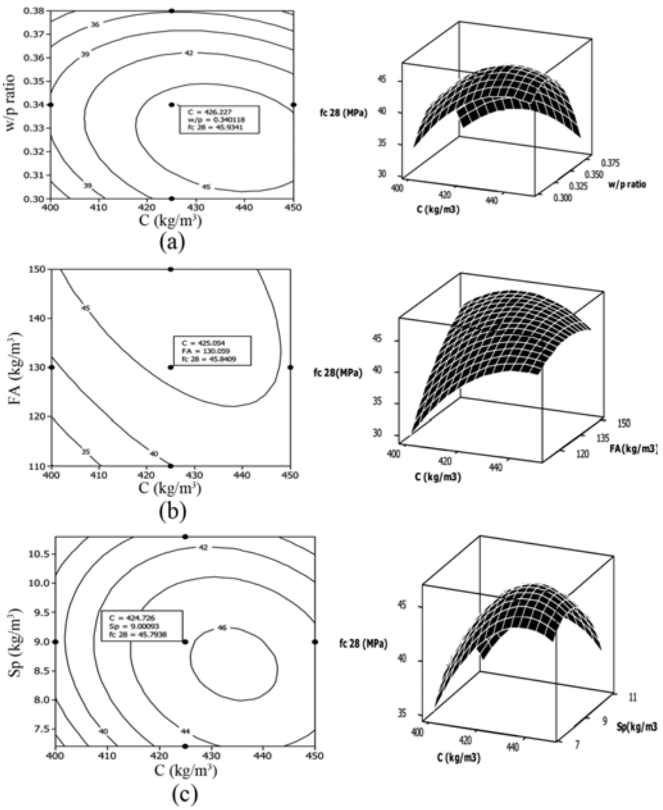


Fig. 4. Response Surface and Contour Plot vs Compressive Strength: (a) Function of Cement (C) and w/p, (b) Function of C and Fly Ash, and (c) Function of C and SP of SCC

5.2 Hardened Properties of SCC

As a graphical optimization for three or fewer responses, contour plots are useful in identifying optimum settings.

In Figs. 4(a), (b), and (c) the graphs show the contour plots obtained from the calculated response surface plots. The fitted surface has a maximum point which refers to cement of 426.2 kg/m^3 at 0.34 w/p and fly ash of 130 kg/m^3 and SP of 9.02 kg/m^3. The model predicted a maximum response of (compressive strength) 45.93 MPa for a 426.2 kg/m^3 cement

In Figs. 5 (a), (b), and (c) the graphs show the contour plots obtained from the calculated response surface plots. The fitted surface has a maximum point which indicates cement of 425 kg/m^3 at 0.34 w/p and fly ash of 130 kg/m^3 and SP of 9 kg/m^3. The model predicted a maximum response of (modulus of elasticity) 33.8 GPa for a 425 kg/m^3 cement.

The effect of cement, water to powder ratio, fly ash and superplasticizers on the hardened properties of SCC (compressive strength and modulus of elasticity) were investigated by response surface methodology.

The experimental values for compressive strength and modulus of elasticity under different treatment conditions are presented in Table 3. The regression coefficients for the second order polynomial equations and results for the full quadratic are presented in Table 5. The statistical analysis indicates that the full quadratic model was adequate, possessing a less significant lack of fit than other models with an R^2 equal to 92.0% for compressive strength and 81.8% for the modulus of elasticity. The effect of cement/powder, fly ash, and, superplasticizer on the hardened properties of SCC can be estimated. A summary of the hardened properties of the full quadratic models of SCC is cited in Table 6.

Khayat *et al*. (2000) used a central composite response surface with 5 factors (w/c ratio (0.37 to 0.5), cement content (360 to 600), viscosity enhancing agent dosage (0.05 to 0.20% by mass of water), superplasticizer dosage (0.30 to 1.10% by mass of binder), volume of coarse aggregate (240 to 400 kg/m^3) and the volume of fine aggregate content varied to achieve volume. Responses studied were slump flow, reheological parameters, filling capacity, V-funnel, surface settlement, and compressive strength at 7 and 28 days.

In comparison, this research used a four factor study consisting of cement content of (400 to 450 kg/m^3), water to powder ratio (0.3 to 0.38), fly ash content (110 to 150 kg/m^3), dosages of superplasticizer (7.1 to 10.8 kg/m^3), the content of fine and coarse aggregate were varied to achieve absolute volume. The responses of V-funnel flow time filling ability, J-ring flow passing ability, stability, and compressive strength at 28 days, and modulus of elasticity were measured.

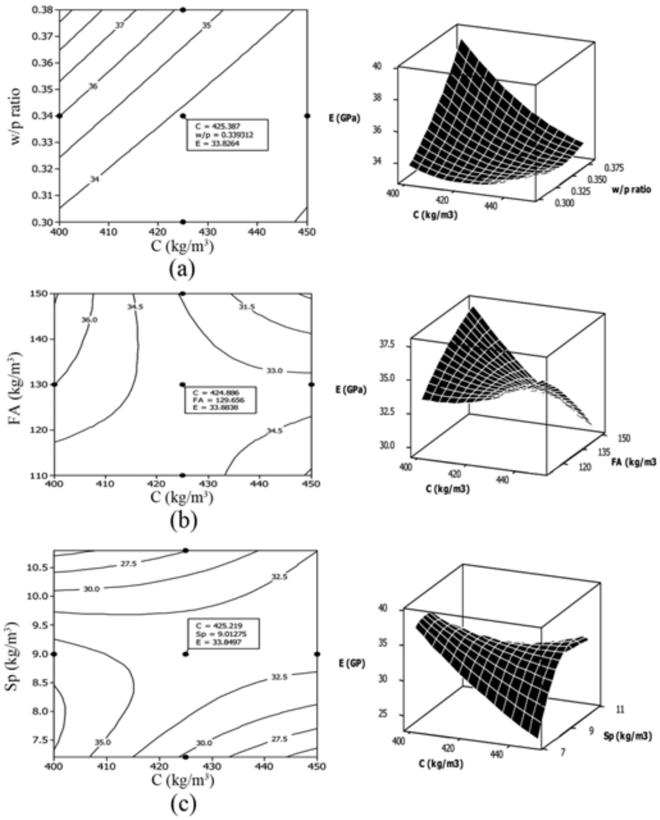


Fig. 5. Response Surface and Contour Plot vs Modulus of Elasticity at 28-days as: (a) Function of Cement and w/p, (b) Function of Cement and Fly Ash, and (c) Function of Cement and SP of SCC

6. Conclusions

The effect of the constitute materials on SCC such as cement, water-powder ratio, fly-ash and superplasticizer on the fresh and hardened properties of the self-compacting concrete were investigated. Based on the result of this research the following conclusions can be drawn:

The statistical model (full quadratic) shows adequacy in possessing with a less significant lack of fit than the other models (linear, interaction, and pure quadratic) with an R^2 of 90.5% for V-funnel, 90.1% for J-ring, 86.2% segregation resistance, 81.8% modulus of elasticity, and 92.0% for compressive strength

The graphical contour plot indicated that the optimum fresh properties for responses are 18.3 seconds for V-funnel, 849 mm J-ring, and 17.8% for segregation resistance with parameters of 425 kg/m^3 cement content, 0.34 w/p ratio, 129 to 130 kg/m^3 fly ash, and 9 kg/m^{3}superplasticizer.

Graphical optimization showed that the responses of compressive strength were 45.93MPa and modulus of elasticity was 33.8GPa fitted at 425 to 426 kg/m^3 cement, 0.34 w/p ratio, 129 to 130 kg/m^3 fly ash, and 9.0 kg/m^3 superplasticizer of SCC.

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