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Statistical Models for Hardened Properties of Self-Compacting Concrete

[1]Arabi N.S. Al Qadi, [1]Kamal Nasharuddin Bin Mustapha,
[2]Hashem Al-Mattarneh and [3]Qahir N.S. AL-Kadi
[1]Department of Civil Engineering, University Tenaga National, Malaysia
[2]Faculty of Engineering, Jerash Private University, Jordan
[3]The Hashemite University, Zarqa, Jordan

Abstract: Problem statement: For predicting workability and hardened properties of Self-Compacting Concrete (SCC) no well known explicit formulation. **Approach:** Statistical models were carried out to model the influence of key mixture parameter (cement, water to powder ratio, fly ash and super plasticizer) on hardened properties affecting the performance of SCC. Such responses included compressive strength at 3, 7 and 28 days and modulus of elasticity. Thirty one mixtures were prepared to derive the numerical models and evaluate the accuracy. The models were valid for a wide range of mixture proportioning. **Results:** The research presented derived numerical models that can be useful to reduce the test procedures and trials needed for the proportioning of self-compacting concrete. The qualities of these models were evaluated based on several factors such as level prediction, residual error, residual mean square and correlation coefficients. **Conclusion:** Full quadratic models in all the response (compressive strength at 3,7 and 28 days and modulus of elasticity) showed high correlation coefficient (R^2), adjusted correlation coefficient, less level of significant and sum of square errors from the four predictions models (linear, interaction, full quadratic and pure quadratic) were developed.

Key words: Hardened SCC, central composite, self-compacting concrete

INTRODUCTION

The mechanical properties and behavior of SCC are similar to conventional concrete in terms of compressive strength. There is some concern that SCC may have a lower modulus of elasticity due to lower coarse aggregate content, which may affect deformation characteristics of pre-stressed concrete members. Additionally, creep and shrinkage are expected to be higher for SCC due to its high paste content, affecting pre-stress loss and long term deflection, although this may be offset in part due to relatively low w/c of SCC commonly used in pre-cast operations.

Previous research: Frank *et al.*[1] Verify the mechanical properties of SCC before using it for practical applications, the time development of the material properties and the bond behavior between the reinforcing bars and the SCC as basis for the description of the load bearing capacity of reinforced concrete structures.

Khatib[2] Study the effect of fly-ash on the properties of SCC by replacement the cement content with 0-80% fly-ash. Fixing the water/binder to 0.36 for all mixes. Testing workability, compressive strength, ultrasonic velocity (uv), absorption and shrinkage. He conclude that a high strength and low shrinkage by the increasing the content of fly ash a 40% replacement of cement gave 65 N mm^{-1} 2 at 56 days, but the high absorption was happen by the increase of fly ash contents a 2% absorption was shown. Also, there is a reduction in shrinkage by the increase of fly ash content. A linear relation ship was happen between fly ash content with 56 days shrinkage and a sharp decrease relation between absorption and strength by increasing absorption 1-2%.

Mehta[3] 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. Three methods for calculating the modulus are used for concrete such as initial tangent modulus, secant modulus and chord modulus.

Vengala[4] found that use of fine fly ash for obtaining Self Compacting Concrete resulted in an increase of the 28 day Compressive Strength Concrete by about 38%. Self Compacting Concrete was achieved when volume of paste was between 0.43 and 0.45. Tests for compressive strength at 3, 7 and 28 days and modulus of elasticity were conducted using Universal Testing Machine (UTM) 1000 KN.

Corresponding Author: Arabi N.S. Al Qadi, Department of Civil Engineering, University Tenaga National, Malaysia

MATERIALS AND METHODS

Materials properties: The materials that implemented in the research are:

Cement: Ordinary Portland cement of available in local market is used in the investigation. The Cement used has been tested for various proportions as per (ASTM C150-85A)[5] the specific gravity was 3.15 and fineness was 2091 $cm^2\ gm^{-1}$.

Coarse and fine aggregate:

Coarse aggregate: Crushed angular granite material of 20 mm max size from a local source was used as course aggregate. The specific gravity of 2.45, absorption value was 1.5%, fineness modulus 6.05 and bulk density of 1480 $kg\ m^{-3}$ confirms to ASTM C 33-86[6] was used. The fine aggregates consisted of river sand with maximum size of 4.75 mm, with a modulus of fineness Mx = 4.16; normal grading. Specific gravity was 2.33 and absorption value was 6.4%.

Fly Ashes (FA): Type-II fly ash from Kapar Thermal Power Station, Selangor, Malaysia, was used as cement replacement material. Fly Ash for use as Pozzolana and Admixture. Class F fly ash was obtained had a specific gravity of 2.323 and fineness of 2423 $cm^2\ g^{-1}$ determined as confirms to (ASTM C 618)[7].

Super Plasticizer (SP): Polycarboxylicether (PCE) based super-plasticizer which is Brown Color and free flowing liquid and having Relative density 1.15 Super Plasticizer confirms to ASTM C 494-92[8]. Type A and Type F in aqueous form to enhance workability and water retention. A sulfonated, naphthalene-formaldehyde super plasticizer and a synthetic resin type Air-Entraining Admixture (AEA) were used in all the concrete mixtures.

Mixing water: Potable water confirms to ASTM D 1129[9] for mixing the concrete and curing of the reaction.

Methods: All concrete mixes were prepared in 40 L batches in a rotating planetary mixer. The batching sequence consisted of homogenizing the sand and coarse aggregate for 30 sec, then adding about half of the mixing water into the mixer and continuing to mix for one more minute. The mixer was covered with plastic cover to minimize the evaporation of the mixing water and to let the dry aggregates in the mixer absorb the water. After 5 min, the cement and fly ash were added and mixed for another minute. Finally, the SP and the remaining water were introduced and the concrete was mixed for 3 min. Nine 100×100×100 mm cubic were cast and moist for each mix to determine compressive strength after 3, 7 and 28 days and 3 cylinder 150×300 mm for modulus of elasticity.

Statistical design of experiment approach: Many researchers have used Design Of Experiment (DOE) techniques to evaluate mix-proportioning effect by selecting trial and optimize proportions. These DOE techniques provide a method to evaluate the effect of different parameters in statically sound manner and with minimum mixture numbers. Models of regression are fitted to the result to each measured response results. A central composite response surface is commonly used approach. Knowledge a bout the materials and proportioning of SCC is required to select the parameters that can be used in the design of experiment and satisfies the SCC characteristics.

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 on the relevant concrete properties. Such two-level factorial design requires a minimum number of tests for each variable[10]. 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 modeled in a quadratic manner. Since the error in predicting the responses increases with the distance from the centre of the modeled 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 composite factorial design, where the effect of each factor is evaluated at five different levels, in codified values of $-\alpha$,-1, 0, 1, $+\alpha$. The value of α value is chosen so that the variance of the response predict by the model would depend only on the distance from the centre of the modeled 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 modeled responses. Appropriate MiTab software was used for statistical analysis of the results[11].

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 experimental levels of the variables (maximum and minimum), boundary of cement content, W/P, fly ash content, Sp dosage are defined.

The modeled experimental region consisted of mixes ranging between the coded variables of -2 to +2 and is given in Table 1. The derived statistical models are valid for mixes with W/P ranging from 0.3-0.38 by mass, dosages of SP ranging from 7.2-10.8 kg m^{-3} 1.8% of total powder content(by mass)[12], cement content ranging from 400-450 kg m^{-3}. The mass of coarse aggregate was 25-35% by volume of the mix. The SCC responses modeled were compressive strengths at 3, 7 and 28 days and modulus of elasticity [13].

RESULTS

Compressive strength is mostly considered as important property of concrete, therefore, the W/P, which affects compressive strength, was chosen to attain the desired strength. In order to achieve high strength, the w/p must be low.

SCC has shown an increase in compressive strength, the values used in Table 2 for the variation of compressive strength with w/p ratio. The strength over 41 obtained for 0.3 and 0.38 water-powder ratios. Relation between modulus of elasticity and compressive strengths.

DISCUSSION

Derived models: The mix proportions and test result of 31 mixes prepared to derive the central composite surface design models are summarized in Table 2 and 3, respectively. The result of the derived models in this research is prepared, along with the correlation coefficients and the relative significance, are in Table 3. The estimates for each parameter refer to the coefficients of the model found by a least-square method. The significant of each variable on a given response is evaluated using t test values based on Student's distribution. Probabilities less than 0.05 are often considered as significant evidence that the parameters are not equal to zero; contribution of the proposed parameter has a highly significant influence on the measured response. The R2 values of the response surface models for the compressive strength 3,

Table 1: Value of coded variables

Coded values	-2	-1	0	1	2
Cement (kg m^{-3})	400.0	412.50	425.00	437.50	450.00
W/P ratio	0.3	0.32	0.34	0.36	0.38
FA (kg m^{-3})	110.0	120.00	130.00	140.00	150.00
SP (kg m^{-3})	7.2	8.10	9.00	9.90	10.80

Table 2: Mix proportions and properties of hardened SCC of all mixes used in the central composite design

	X1	X2	X3	X4			Y9	Y10	Y11	Y12
No.	Cement (kg m^{-3})	W/P (ratio)	FA (kg m^{-3})	SP (kg m^{-3})	Sand (kg m^{-3})	CA (kg m^{-3})	$f_{C3(Mpa)}$	$f_{C7(Mpa)}$	$f_{C28(Mpa)}$	E (Gpa)
1	425.0	0.38	130	9.0	861	693	19.876	27.593	35.254	27.890
2	450.0	0.34	130	9.0	869	700	25.877	32.534	47.095	32.862
3	412.5	0.36	120	9.9	898	723	16.739	25.768	36.235	31.950
4	437.5	0.32	140	9.9	884	712	22.829	29.590	46.484	34.926
5	437.5	0.36	120	8.1	877	706	23.520	31.800	44.307	37.865
6	412.5	0.32	140	8.1	909	731	24.564	33.973	45.216	38.943
7	425.0	0.34	130	9.0	892	718	9.7250	35.058	48.975	37.494
8	425.0	0.34	130	9.0	892	718	11.900	29.050	44.543	32.752
9	425.0	0.34	130	9.0	892	718	12.230	30.200	45.102	30.473
10	425.0	0.34	150	9.0	870	701	27.366	36.939	48.174	32.096
11	437.5	0.32	140	8.1	887	714	29.103	30.059	47.181	28.886
12	437.5	0.32	120	9.9	905	728	24.250	32.895	41.927	32.320
13	437.5	0.36	120	9.9	874	704	22.340	29.678	39.152	33.798
14	437.5	0.32	120	8.1	907	730	27.075	37.814	45.997	30.589
15	437.5	0.36	140	9.9	853	686	20.324	28.978	37.573	31.576
16	412.5	0.36	140	8.1	878	707	19.688	27.262	40.747	36.931
17	425.0	0.34	110	9.0	913	735	10.679	30.116	38.587	34.138
18	412.5	0.36	140	9.9	876	705	14.639	33.472	44.732	38.401
19	425.0	0.34	130	9.0	892	718	12.906	28.359	43.337	29.939
20	412.5	0.36	120	8.1	900	725	11.637	28.648	37.051	39.026
21	437.5	0.36	140	8.1	855	688	21.672	30.583	41.055	30.742
22	425.0	0.30	130	9.0	922	742	23.456	33.795	42.657	34.345
23	425.0	0.34	130	7.2	894	720	23.760	31.843	42.433	29.284
24	412.5	0.32	140	9.9	906	729	21.192	31.017	40.734	31.288
25	425.0	0.34	130	9.0	892	718	9.9200	32.237	46.833	36.234
26	425.0	0.34	130	9.0	892	718	10.832	34.051	47.752	34.789
27	425.0	0.34	130	9.0	892	718	11.300	31.000	46.200	33.716
28	425.0	0.34	130	10.8	889	716	16.896	30.013	41.056	27.214
29	412.5	0.32	120	8.1	929	748	17.778	26.494	41.451	29.815
30	412.5	0.32	120	9.9	927	746	9.1360	23.958	38.457	38.457
31	400.0	0.34	130	9.0	914	736	10.745	22.050	35.995	35.995

Table 3: Statistical models of compressive strength at 3, 7 and 28 days and modulus of elasticity summary

Model	R^2 (%)	R^2 AdJ. (%)	F-value	P-value	Resid. lower	SSE	Residupp.	Regression equation
Linear								
$f_{C28\ (Mpa)}$	46.6	38.30	5.66	0.002	-4.043	253.000	5.097	Y11 = 1.3+0.138×1-86.3×2+0.160×3- 0.947×4
$f_{C7\ (Mpa)}$	33.5	23.20	3.27	0.027	-4.661	241.621	5.313	Y10 = -18.5+0.139×1-45.9×2+0.0897×3-0.692×4
$f_{C3\ (Mpa)}$	45.7	37.30	5.47	0.002	-8.467	637.420	5.763	Y9 = - 94.8+0.287×1- 67.8×2+0.229×3-1.73×4
E (Gpa)	11.7	0.00	0.86	0.501	-5.813	309.620	5.228	Y12 = 80.0-0.101×1+4.5×2-0.0259×3-0.195×4
Interaction								
$f_{C28\ (Mpa)}$	55.4	33.10	2.49	0.040	-4.062	211.580	6.320	Y11 = -1040+2.77 ×1+1200×2+3.79×3+5.0×4- 3.10×1×2- 0.00866×1×3- 0.0505×1×4 -1.38×2×3 +23.5 ×2×4 + 0.0580 ×3×4
$f_{C7\ (Mpa)}$	60.5	40.80	3.06	0.016 h	-5.012	143.420	4.602	Y10 = -1192+3.45×1+548×2+6.33×3-9.0×4- 2.26×1×2- 0.0169×1×3-0.0386×1×4+0.29×2×3 +36.4×2×4+0.0947×3×4
$f_{C3\ (Mpa)}$	53.9	30.80	2.34	0.051	-8.467	541.320	5.982	Y9 = -1170+2.56×1+632×2+8.57×3-16.8×4- 1.36×1×2 -0.0140×1×3+0.002×1×4 -5.43×2×3+ 64.7×2×4 -0.059×3×4
E (Gpa)	23.7	0.00	0.62	0.778	-5.813	267.410	4.830	Y12 = -436+0.45×1+931×2+3.85×3-2.4×4- 0.14×1×2 -0.00738×1×3+0.0509×1×4 -2.45×2×3 - 61.1×2×4+0.010×3×4
Full quad.								
$f_{C28\ (Mpa)}$	82.3	66.90	5.33	0.001	-3.055	83.7950	2.869	Y11 = - 2992+8.65 ×1+4136×2+5.40×3+27.9×4 - 3.10 ×1×2 -0.00866 ×1×3 -0.0505×1×4-1.38 ×2×3+23.5×2×4+0.0580×3×4 - 0.00691×1×1 - 4318 ×2×2-0.00621×3×3-1.27×4×4
$f_{C7\ (Mpa)}$	73.2	49.80	3.13	0.016	-3.034	97.1700	3.636	Y10 = -2500+9.51×1+995×2+5.17×3-4.4×4- 2.26×1×2-0.0169×1×3- 0.0386 ×1×4+0.29×2×3 + 36.4×2×4+0.0947×3×4-0.00713×1×1-658 ×2×2+0.00445×3×3-0.253×4×4
$f_{C3\ (Mpa)}$	92.0	85.00	13.19	0.000	-4.150	93.5590	3.306	Y9 = 2332-7.56×1-3953×2+3.27×3-69.4 4- 1.36×1×2-0.0140×1×3+0.0019×1×4 -5.43×2×3 + 64.7×2×4 -0.0590×3×4+0.0119×1×1+6743 ×2×2+ 0.0204×3×3+2.92×4×4
E (Gpa)	36.3	0.00	0.65	0.788	-4.985	223.45	5.290	Y12 = 134-2.79×1+1328×2+3.16×3+18.8×4- 0.14×1×2-0.00738×1×3+0.0509×1×4 -2.45×2×3 - 61.1×2×4+0.010×3×4+0.00380×1×1-583 ×2×2+0.00267×3×3-1.17×4×4
Pure quad.								
$f_{C28(Mpa)}$	73.5	63.80	7.62	0.000	-4.813	125.808	1.649	Y11 = -1951+6.01×1+2850×2+1.77×3+21.9 ×4- 0.00691×1×1 - 4318×2×2-0.00621×3×3-1.27×4×4
$f_{C7(Mpa)}$	46.2	26.60	2.36	0.053	-4.404	195.371	5.569	Y10 = -1326+6.20×1+401×2-1.07×3+3.9×4- 0.00713×1×1-658×2×2+0.00445×3×3 -0.253×4×4
$f_{C3(Mpa)}$	83.8	78.00	14.26	0.000	-4.150	189.650	5.306	y9 = 3407- 9.82×1-4653×2-5.07×3-54.2 ×4+ 0.0119×1×1+6743×2×2+0.0204×3×3+2.92×4×4
E (Gpa)	24.2	0.00	0.88	0.549	-4.985	265.660	4.544	Y12 = 650-3.34×1+401×2-0.72×3+20.9×4+ 0.00380×1×1-583×2×2+0.00267×3×3-1.17×4×4

7 and 28 day fc and modulus of elasticity are 92, 73.2, 82.3 and 36.3% in full quadratic equation with respect to the linear, interaction and pure quadratic. The high correlation coefficient of the response shows good correlations that considered at least 95% of the measured values can be accounted for proposed models. The accuracy of the proposed models was determined by comparing predicted to measured values

Correlation between measured and predicted models: The response surface methodology was used to investigate the effect of parameters (cement, W/P, FA and SP) on hardened properties (compressive strength at 3,7 and 28 days and modulus of elasticity). The levels of independent parameters were determined based on preliminary experiments as shown in Table 1.

The experimental values for compressive strength at 3, 7 and 28 days and modulus of elasticity under different treatment conditions are presented in Table 2. Regression coefficient for polynomial equations and result of linear, interaction, full and pure quadratic are presented in Table 3.

Statistical analysis for compressive strength at 28 days indicates that the models with coefficient of correlation R^2 for linear, interaction full and pure quadratic are 46.6, 55.4,82.3 and 73.5 Shows that the full quadratic at R^2 equal to 82.3 was adequate, possessing less significant lack of fit than other model the better one fit shown in Fig. 1.

Moreover, compressive strength at 7 days indicate that the models of R^2 = 33.5, 60.5, 73.2 and 46.2 for linear, interaction, full and pure quadratic.

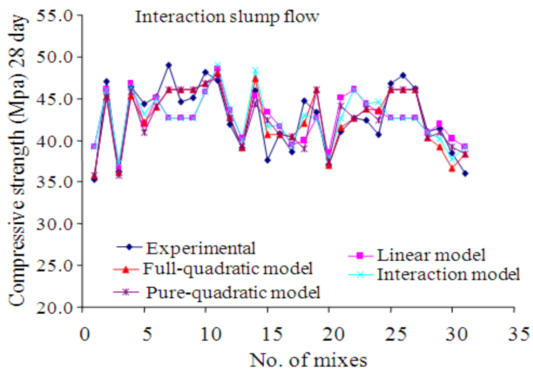

Fig. 1: Comparison between measured compressive strength at 28 days and predicted values from statistical models

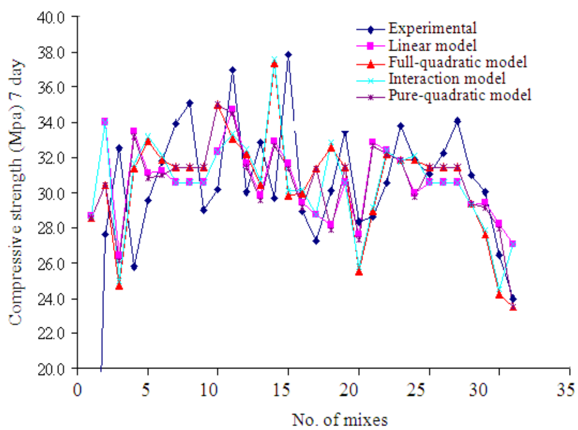

Fig. 2: Comparison between measured compressive strength at 7 days and predicted values from statistical models

The closer value to unity is a full quadratic model with $R^2 = 73.2\%$ is better model fit as shown in Fig. 2.

QQ, full and pure quadratic models full quadratic show in Fig. 3 the best fit.

Furthermore, modulus of elasticity statistical models with R^2 values of the response surface models for linear, interaction, full and pure quadratic models were found to be 11.7, 23.7, 36.3 and 24.2 as shown in Fig. 4 with the best fit is a full quadratic model.

Residuals models: Residual is the measure of the deviation of an observed data point from the estimated regression line. If the estimated regression line fits the data points perfectly, error sum of squares (SSE) = 0. The more the line the variability of the data points away from the line, the larger the value for SSE[14].

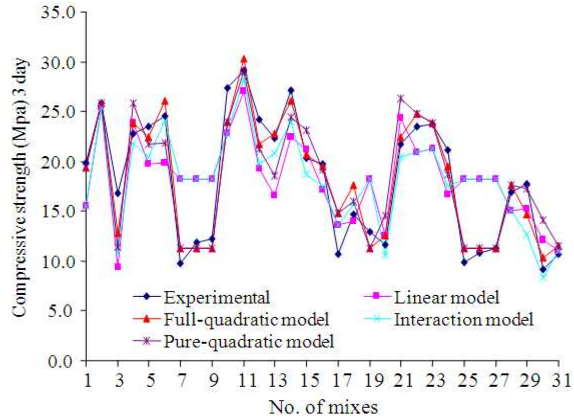

Fig. 3: Comparison between measured compressive strength at 3 days and predicted values from statistical models

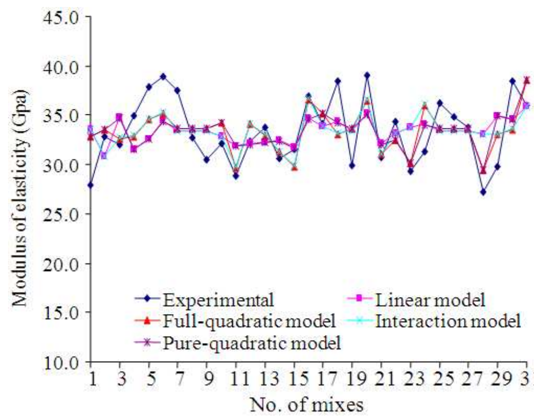

Fig. 4: Comparison between measured modulus of elasticity and predicted values from statistical models

Figure 5 the data of compressive strength at 28 days measured and predicted values of SSE equals to 253,211.58, 83.795 and 125.808 for linear, interaction, full and pure quadratic models indicate that full quadratic less variability of the data point from the line than other models. Therefore, Fig. 6 analyses of data of $f_{c'}$ at 7 days, SSE equal to 241.621, 143.42.97.17 and 195.371 four the polynomial models indicate that full quadratic is fit than other models.

Thus, Fig. 7 the data of $f_{c'}$ at 3 days the SSE equals to 637.42, 541.32, 93.559 and 189.65 indicate the best is at full quadratic model. Result of Fig. 8 for modulus of elasticity indicate that SSE = 309.62, 267.41, 223.45 and 265.66 the full quadratic is the best one.

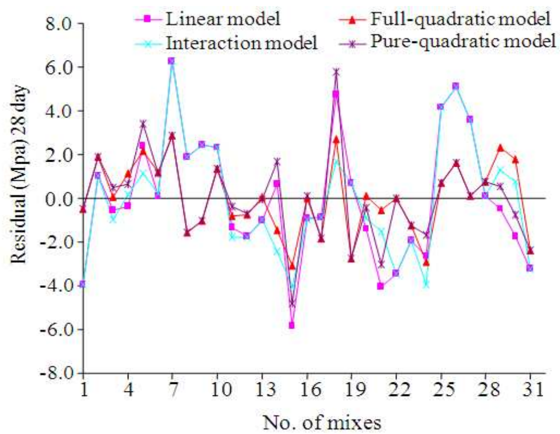

Fig. 5: Residual compressive strength at 28 days for various statistical models

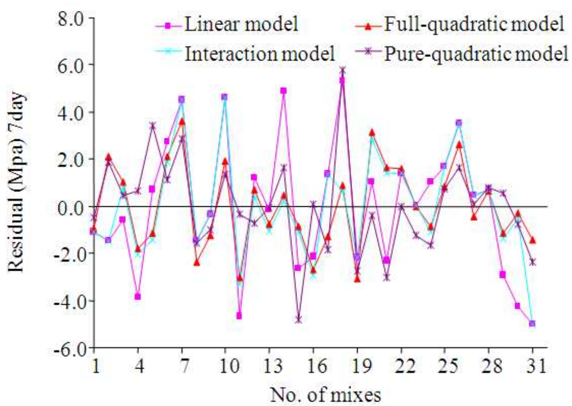

Fig. 6: Residual compressive strength at 7days for various statistical models

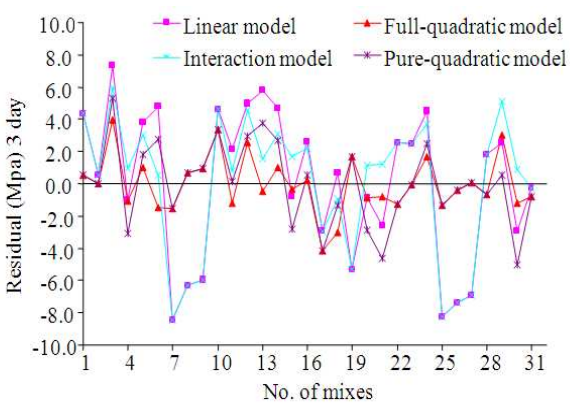

Fig. 7: Residual compressive strength at 3 days for various statistical models

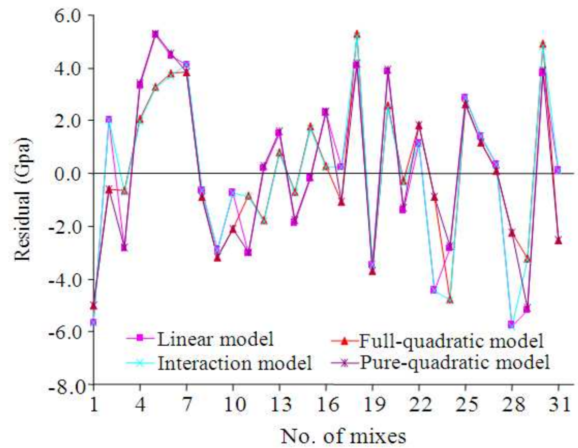

Fig. 8: Residual modulus of elasticity for various statistical models

CONCLUSION

The effect of the concrete constituents such as cement, water-powder ratio, fly-ash and super-plasticizer on hardened properties of self-compacting concrete were investigated based on the result of this research the following conclusions can be drawn:

- A central composite design is a useful tools to evaluate parameters effects of mixture and the interaction between the parameters on SCC that can reduce the number of trials to achieve balance among mix variables
- Numerical models established for the SCC mixtures can be useful in design of concrete and selecting constituent materials
- Central composite was selected where the response modeled in a quadratic manner while seven replicate central points were prepared to estimate the degree of experimental error response model
- Graphical analysis of the residuals shows the deviation between the measured data and the fit one could be effective methods to test the adequacy of the regression model fit
- Fluctuating of measured residual data in random manner show a satisfactory plot on the band and its clear in full quadratic models for all the sixteen models

Full quadratic models in all the response (compressive strength at 3,7 and 28 days and modulus of elasticity) shows a high correlation coefficient (R^2), adjusted correlation coefficient, less level of significant and sum of square errors from the four predictions models (linear, interaction, full quadratic and pure quadratic) were developed

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