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Central Composite Design Models for Workability and Strength of Self-Compacting Concrete

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Abstract: A central composite design models was carried out to model the influence of key mixture parameter on fresh and hardened properties affecting the performance of Self-Compacting Concrete (SCC). Such responses included slump flow as a filing ability, L-Box as a passing ability and sieve analysis as resistance to segregation. Thirty-one mixtures were prepared to derive the numerical models and evaluate the accuracy. The models are valid for a wide range of mixture proportioning. The study presents, the 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.

Key words: Workability, statistical models, self-compacting concrete, design model, numerical models, strength

INTRODUCTION

Sonebi (2004) in his study investigated and developed medium strength SCC by using pulverized fuel ash and (SP). In his analysis used factorial design to get mathematical models on five parameters. The parameters were cement, PFA (W/P) and SP. Also, the responses of the statistical models are slump flow, fluidity, loss orimet time, V-funnel time, L = box, JRing combined to the orimet, JRing combined to the cone, rheological parameter, segregation and compressive strength at 7, 28 and 90 days. The developed models were valid with 0.38-0.72 W/P, 60-216 kg m^{-3} of cement, 183-317 kg m^{-3} of PFA and 0-1% by mass of powder. The results showed that MS-SCC at 28 day compressive strength can achieve to 30-35 MPa by using 211 kg m^{-3}.

Prasad *et al*. (2008) were used Artificial Neural Network (ANN) to predict a 28 days compressive strength on SCC and normal concrete and addition of high fly-ash and they found that the proposed ANN are validated by estimation of slump flow and compressive strength of SCC.

Felekoglu *et al*. (2007) they are focusing on the development of mix design of SCC and making adjustment to W/C ratio and the dosage of SP. The parameters are five mixtures were investigated, the responses are slump flow, V-funnel and L-Box was carried to determine optimum parameters for SCC mixtures. The hardened properties of SCC were studied also.

Domone (2007) in his studied 70 paper on hardened properties of Self Compacting Concrete (SCC) the data were analyzed and relations between the cylinder and cubic compressive and tensile strengths and modulus of elasticity.

The conclusions were addition of limestone powder makes a substantial contribution to strength and the performance of structural elements is largely predicted by properties of materials measured and analysis of the data were enough to give confidence for SCC.

Laboratory test, such as the Slump flow, Sieve Size, L-Box and 28 days compressive strength tests were conducted using indigenous materials Malaysia.

MATERIALS AND METHODS

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) (ASTM Standard C 150, 2006) 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 (ASTM C 33-03, 2006) was used.

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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) (ASTM C 618-05, 2006).

Superplasticizer (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 (ASTM C494/C494M-05a, 2006). 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.

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.

Slump flow, L-Box, V-funnel were used to test the workability, passing ability of SCC. With the L-Box, the height of concrete in the vertical part, after the flowing of concrete, was considered in the analysis of the results. The resistance to segregation was measured by sieve size, a fresh concrete was poured from 2 kg panel over sieve number 5 to observe the quantity of concrete passing the sieve after 5 min (Sonebi, 2004). Nine 100×100×100 mm cubic were cast and moist for each mix to determine compressive strength after 3, 7 and 28 days.

Development of statistical models: Statistical experimental design of four factors at two levels was used to evaluate the influence of 2 different levels for each variable on the relevant concrete properties. Such 2 level factorial design requires a minimum number of tests for each variable (Montgomery, 2005). 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 -α to +α limits.

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

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 -α, -1, 0, 1, +α. 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 as shown in Table 1. Appropriate MiniTab software was used for statistical analysis of the results (MINITAB Handbook, 2003).

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) (Su *et al.*, 2001), 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 slump flow, L-Box ratio, segregation resistance and 28 day compressive strengths (EFNARC, 2002).

RESULTS AND 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. 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 <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 R^2 values of the response surface models for the slump flow, L-Box, resistance to segregation and 28 days f_c are 80.8, 55.9, 60.6 and 82.3% 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. Table 2 shows, the mix proportions and properties of fresh and hardened SCC of all mixes used in the central composite design.

Numerical models for slump flow (mm) y1, compressive strength (Mpa) Y11, L-Box (ratio) y4, segregation resistance (%) y8: The linear, interaction, full and pure quadratic models for slump flow, compressive strength at 28 days, Lox and resistance to segregation are shown in Table 3 with values of R^2, R^2-adj., F and p-values and Lowe and upper values of Residuals. As shown in the Fig. 1, the residuals of slump flow linear model plot versus

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

Number	Cement (kg m^{-3}) X1	W/P (ratio) X2	FA (kg m^{-3}) X3	SP (kg m^{-3}) X4	Sand (kg m^{-3}) X4	CA (kg m^{-3}) X4	Slump flow (mm) Y1	L-Box (ratio) Y4	SR (%) Y8	f_{C28} (Mpa) Y11
1	425	0.38	130	9	861	693	930.000	0.978	33.000	35.254
2	450	0.34	130	9	869	700	905.000	0.875	43.000	47.095
3	412.5	0.36	120	9.9	898	723	890.000	0.833	30.000	36.235
4	437.5	0.32	140	9.9	884	712	885.000	0.938	20.700	46.484
5	437.5	0.36	120	8.1	877	706	925.000	0.988	22.000	44.307
6	412.5	0.32	140	8.1	909	731	840.000	1.632	20.000	45.216
7	425	0.34	130	9	892	718	920.000	1.410	28.000	48.975
8	425	0.34	130	9	892	718	848.000	0.997	18.510	44.543
9	425	0.34	130	9	892	718	862.000	1.030	21.253	45.102
10	425	0.34	150	9	870	701	835.000	1.059	19.000	48.174
11	437.5	0.32	140	8.1	887	714	728.000	1.056	5.500	47.181
12	437.5	0.32	120	9.9	905	728	830.000	0.976	7.300	41.927
13	437.5	0.36	120	9.9	874	704	850.000	0.980	18.000	39.152
14	437.5	0.32	120	8.1	907	730	730.000	0.940	6.000	45.997
15	437.5	0.36	140	9.9	853	686	820.000	0.997	10.000	37.573
16	412.5	0.36	140	8.1	878	707	833.000	0.940	18.000	40.747
17	425	0.34	110	9	913	735	740.000	0.989	12.200	38.587
18	412.5	0.36	140	9.9	876	705	739.000	0.940	12.400	44.732
19	425	0.34	130	9	892	718	840.000	0.990	17.500	43.337
20	412.5	0.36	120	8.1	900	725	801.500	0.920	17.400	37.051
21	437.5	0.36	140	8.1	855	688	847.500	0.106	36.700	41.055
22	425	0.3	130	9	922	742	830.000	0.103	20.000	42.657
23	425	0.34	130	7.2	894	720	765.000	0.933	7.900	42.433
24	412.5	0.32	140	9.9	906	729	790.500	0.950	17.200	40.734
25	425	0.34	130	9	892	718	880.000	1.240	24.900	46.833
26	425	0.34	130	9	892	718	900.000	1.350	26.100	47.752
27	425	0.34	130	9	892	718	870.000	1.200	23.000	46.200
28	425	0.34	130	10.8	889	716	777.500	0.988	16.400	41.056
29	412.5	0.32	120	8.1	929	748	625.000	0.379	0.110	41.451
30	412.5	0.32	120	9.9	927	746	667.500	0.892	1.000	38.457
31	400	0.34	130	9	914	736	720.000	0.967	7.400	35.995

Table 3: Statistical models of slump flow, compressive strength at 28 days, L-Box and resistance to segregation summary

Model	R^2 (%)	R^2adj. (%)	F-value	p-value	Residual lower	Residual upper	Regression equation
Linear							
Slump flow (mm)	34.6	24.5	3.44	0.022	-106.4	99.9	y1 = -1147 + 2.66×1 + 1688×2 + 1.48×3 + 7.7×4
Comp.st.fc_{28} (Mpa)	46.6	38.3	5.66	0.002	-4.043	5.097	Y11 = 1.3 + 0.138×1 - 86.3×2 + 0.160×3 - 0.947×4
L-Box	3.0	0.0	0.20	0.936	-0.7935	0.6724	y4 = 0.74 - 0.00230×1 + 1.44×2 + 0.00330×3 + 0.0303×4
Segregation Resistance (%)	30.7	20.1	2.89	0.042	-18.15	18.15	y8 = - 209 + 0.271×1 + 235×2 + 0.218×3 + 0.37×4
Interaction							
Slump flow (mm)	57.7	36.6	2.73	0.027	-79.3	99.9	y1 = -21426 + 18.1×1 + 45525×2 + 136×3 + 190×4 - 17.8×1×2 - 0.137×1×3 + 0.93×1×4 - 193×2×3 - 1243×2×4 - 1.18×3×4
Compressive strength at 28 days (Mpa)	55.4	33.1	2.49	0.040	-4.062	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
L-Box	32.2	0.0	0.86	0.579	-0.7935	0.3959	y4 = -81.8 + 0.142×1 + 121×2 + 0.725×3 - 3.37×4 - 0.155×1×2 - 0.00111×1×3 + 0.00587×1×4 - 0.665×2×3 + 3.64×2×4 - 0.00252 ×3×4
Segregation resistance (%)	44.0	16.0	1.57	0.187	-17.11	18.15	y8 = -1801 + 0.55×1 + 3021×2 + 8.33×3 + 119×4 + 1.93×1×2 + 0.0003×1×3 - 0.107×1×4 - 18.5×2×3 - 133×2×4 - 0.213×3×4

Table 3: Continued

Model	R^2 (%)	R^2adj. (%)	F-value	p-value	Residual lower	Residual upper	Regression equation
Full quadratic							
Slump flow (mm)	80.8	64.1	4.82	0.002	-87.5	89.17	y1 = -48682 + 114×1 + 46691×2 + 198×3 + 809×4 - 17.8×1×2 - 0.136×1×3 + 0.93×1×4 - 193×2×3 - 1243×2×4 - 1.18×3×4 - 0.112 ×1×1 - 1715×2×2 - 0.238×3×3 - 34.4×4×4
Compressive strength at 28 days (Mpa)	82.3	66.9	5.33	0.001	-3.055	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
L-Box	55.9	17.3	1.45	0.236	-0.4273	0.3515	y4 = -200 + 0.447×1 + 378×2 + 0.804×3 - 2.35×4 - 0.155×1×2 - 0.00111×1×3 + 0.00587×1×4 - 0.665×2×3 + 3.64×2×4 - 0.00252 ×3×4 - 0.000359×1×1 378×2×2 - 0.000303×3×3 - 0.0571×4×4
Segregation resistance (%)	60.6	26.2	1.76	0.139	-15.75	14.17	y8 = -2733 + 1.50×1 + 2765×2 + 15.0×3 + 195×4 + 1.93×1×2 + 0.0003×1×3 - 0.107×1×4 - 18.5×2×3 - 133×2×4 - 0.213×3×4 - 0.0011×1×1 + 377×2×2 - 0.0257×3×3 - 4.24×4×4
Pure quadratic							
Slump flow (mm)	57.7	42.3	3.75	0.007	87.5	94.9	y1 = -28403 + 98.2×1 + 2854×2 + 63.4×3 + 627×4 - 0.112×1×1 - 1715×2×2 - 0.238×3×3 - 34.4×4×4
Compressive strength at 28 days (Mpa)	73.5	63.8	7.62	0.000	-4.813	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
L-Box	28.7	2.8	1.11	0.395	-0.7365	0.7365	y4 = -117 + 0.303×1 + 259×2 + 0.082×3 + 1.06×4 - 0.000359 ×1×1 - 378×2×2 - 0.000303×3×3 - 0.0571×4×4
Segregation resistance (%)	47.4	28.2	2.47	0.044	-17.31	14.17	y8 = -1141 + 1.22×1 - 21×2 + 6.91×3 + 76.7×4 - 0.0011×1×1 + 377×2×2 - 0.0257×3×3 - 4.24×4×4

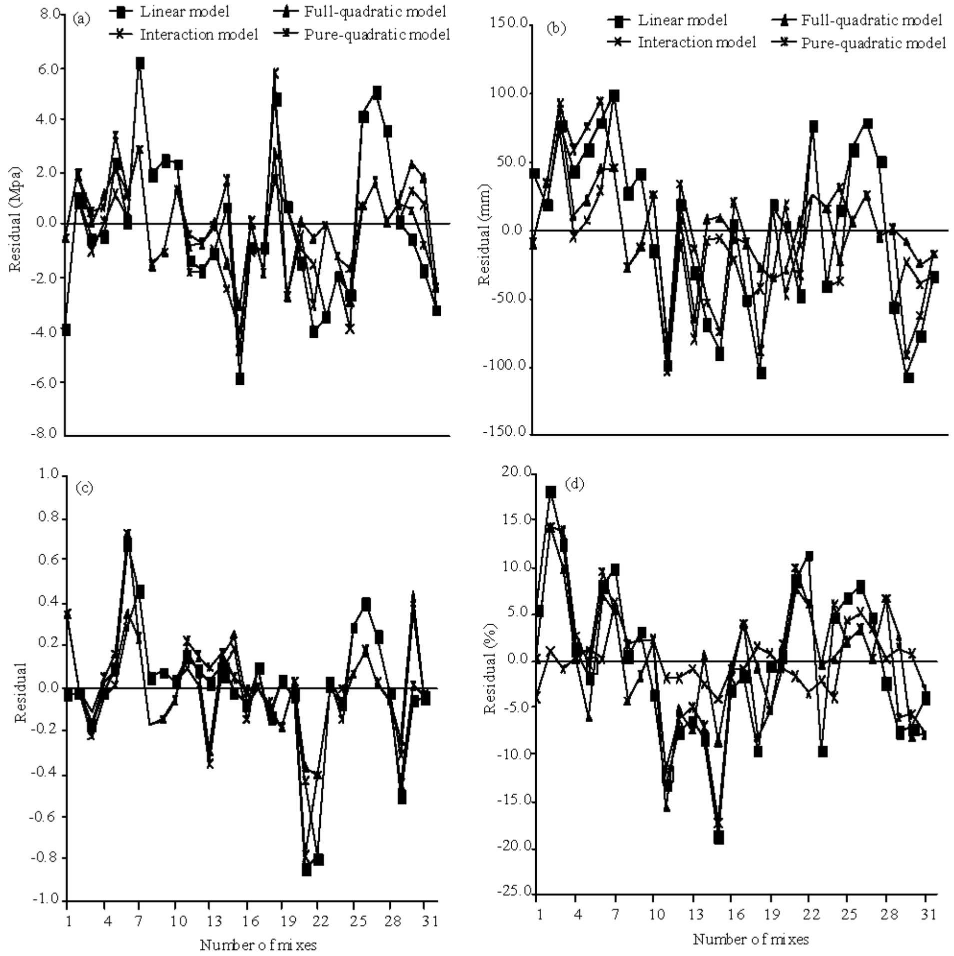

Fig. 1: Residual of workability (slump flow, L-Box and segregation resistance) and compressive strength at 28 days for various statistical model

the run order fluctuate in a random pattern around the center line. The range of residual varies between -106.4 and 99.9.Also, for interaction model -103.3 to 99.9, full quadratic model -87.5 to 89.17 and pure quadratic -83.7 to 94.9. Linear model show high residual range which indicates a poor fit. The adjusted correlation coefficient a 80.8% and the adjusted $R^2$64.1 that fits the data full quadratic model with a significant p-value approach to zero better than other models.

Moreover, the residuals of compressive strength linear model plot versus the run order fluctuate in a random pattern around the center line. The range of residual varies between -4.043 and 5.097 for linear. Also, for interaction model -4.062 to 6.320, full quadratic model -3.055 to 2.869 and pure quadratic -4.813 to 1.649. Interaction model show high residual range which indicates a poor fit as shown in Fig. 1. The adjusted correlation coefficient and 82.3% and the adjusted correlation coefficient 66.9% that fits the data of model full quadratic with a significance value that is very close to zero, Fig. 2, which is more significant and better than other models.

In addition, the residuals of L-Box linear model plot versus the run order fluctuate in a random pattern around the center line.

The range of residual varies between -0.7935 and 0.6724 for linear. Also, for interaction model -0.7935 to 0.3959, full quadratic model -0.4273 to 0.3515 and pure quadratic -0.7365 to 0.7365. Pure quadratic model show high residual range, which indicates a poor fit as shown in Fig. 1.

The adjusted correlation coefficient a 55.9% and the adjusted correlation coefficient 17.3% that fits the data of model full quadratic with a significance value that is close to zero than other values in Fig. 2, which is more significant and better than other models.

Furthermore, the residuals of segregation resistance linear model plot versus the run order fluctuate in a random pattern around the center line. The range of residual varies between -18.15 and 18.15 for linear. Also, for interaction model -17.11 to 18.15, full quadratic model -15.75 to 14.17 and pure quadratic -17.31 to 14.17. Linear model show high residual range which indicates a

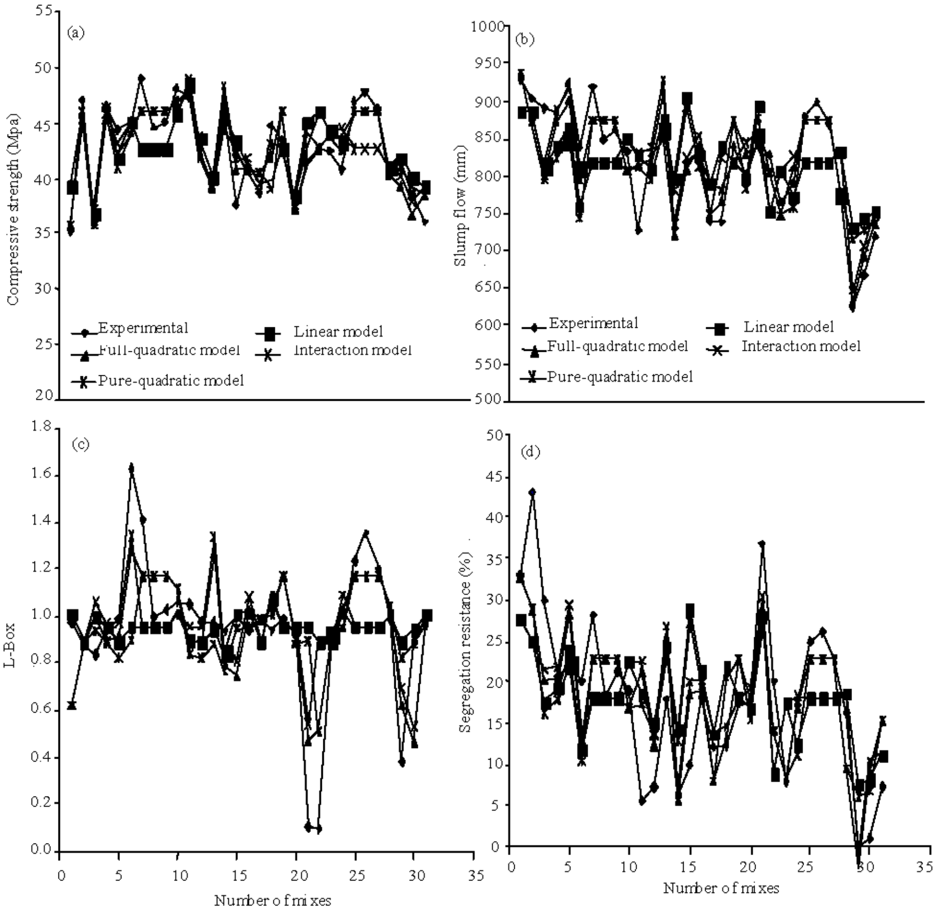

Fig. 2: Comparison between measured workability and strength and predicted value from statistical models

poor fit. The adjusted correlation coefficient a 60.6% and the adjusted correlation coefficient 26.2%, that fits the data of model full quadratic with a significance value that is close to zero than other values in Fig. 2, which is more significant and better than other models.

CONCLUSION

The effect of the concrete constituents such as cement, water-powder ratio, fly-ash and super-plasticizer on workability of concrete and compressive strength 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 and its clear in Fig. 2
- Full quadratic models in all the response (slump flow, L-Box, segregation resistance and 28 days compressive strength) shows a high correlation coefficient (R^2) and adjusted correlation coefficient and less level of significant from the four predictions models (linear, interaction, full quadratic and pure quadratic) were developed

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