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Medium strength self-compacting concrete containing fly ash: Modelling using factorial experimental plans

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Abstract

Fresh self-compacting concrete (SCC) flows into place and around obstructions under its own weight to fill the formwork completely and self-compact, without any segregation and blocking. The elimination of the need for compaction leads to better quality concrete and substantial improvement of working conditions. SCC mixes generally have a much higher content of fine fillers, including cement, and produce excessively high compressive strength concrete, which narrows its field of application to special concrete only. To obtain maximum benefit from SCC, it has to be adopted in general concrete construction practice. Such practice requires inexpensive and medium strength concrete.

This investigation aims to develop medium strength SCC (MS-SCC). The cost of materials will be decreased by reducing the cement content and by using pulverised fuel ash (PFA) with a minimum amount of superplasticizer (SP). A factorial design was carried out to mathematically model the influence of five key parameters on filling and passing abilities, segregation and compressive strength, which are important for the successful development of medium strength self-compacting concrete incorporating PFA. The parameters considered in the study were the contents of cement and PFA, water-to-powder (cement + PFA) ratio (W/P) and dosage of SP. The responses of the derived statistical models are slump flow, fluidity loss, Orimet time, V-funnel time, L-box, JRing combined to the Orimet, JRing combined to cone, rheological parameters, segregation and compressive strength at 7, 28 and 90 days. Twenty-one mixes were prepared to derive the statistical models, and five were used for the verification and the accuracy of the developed models. The models are valid for mixes made with 0.38 to 0.72 W/P, 60 to 216 kg/m^3 of cement content, 183 to 317 kg/m^3 of PFA and 0% to 1% of SP, by mass of powder. The influences of W/P, cement and PFA contents, and the dosage of SP were characterised and analysed using polynomial regression, which can identify the primary factors and their interactions on the measured properties. The results show tha MS-SCC can be achieved with a 28-day compressive strength of 30 to 35 MPa by using up to 210 kg/m^3 of PFA.

Keywords: Fly ash; Rheology; Segregation; Self-compacting concrete; Slump flow

1. Introduction

Self-compacting concrete (SCC) is a new category of high-performance concrete characterised by its ability to spread into place under its own weight without the need of vibration, and self-compact without any segregation and blocking. The introduction of SCC represents a major technological advance, which leads to a better quality of concrete produced and a faster and more economical concrete construction process. SCC was first developed in Japan 12 years ago, and was adopted in Europe, North America and the rest of the world. The elimination of the need for compaction may lead to better quality concrete; economic efficiency (increased casting speed and reduction in labour, energy, and cost of equipment); enhancement towards the automation of precast products; and substantial improvement of working conditions (high consumption of industrial by-products and reduced noise and health hazards) [1–5].

The first generation of SCC used in the UK and Europe, such as the one developed in a large European research project, which investigated the practicability of using SCC in both civil engineering and in building structures, contained a high dosage of powder, as well as a high dosage of superplasticizer (SP), to ensure adequate filling ability and passing abilities and segregation resistance [5]. Savings in labour costs might offset the increased cost related to the use of more cement and SP, but the use of

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mineral admixtures, such as pulverised fuel ash (PFA), ground granulated blast slag (GGBS) or limestone powder (LSP), could increase the fluidity of the concrete, without any increase in the cost. The incorporation of PFA, or GGBS or LSP reduced the requirement of SP necessary to obtain a similar slump flow compared with the same concrete containing only cement [6–8]. These supplementary materials also enhanced the rheological parameters [8] and reduced the risk of the cracking of concrete due to the heat of hydration, and therefore improved the durability [9,10].

The second generation of SCC incorporating a low content of powder, such as LSP, was investigated using an experimental design method to characterise the slump flow, V-funnel test, the rheological parameters, settlement and compressive strength [11]. The replacement of a large volume of cement by 100 kg/m^3 of LSP is shown to reduce the cement content needed to achieve a given slump flow, viscosity, and compressive strength at early age. Such concrete can exhibit a greater resistance to surface settlement compared with similar concrete with low dosage of LSP [11]. Other researchers [9,12,13] evaluated the properties of SCC incorporating high volumes of fly ash to reduce the cost of SCC. An economical SCC mix, made with 50% of fly ash and water-to-powder ratio (W/P) of 0.45, and having a 28-day compressive strength of 35 MPa, was reported [12].

The objective of this paper is to investigate the feasibility of using a factorial design method to identify the relative significance of primary mix parameters and their coupled effects on the relevant properties of medium strength SCC (MS-SCC), to reduce the cost of SCC and encourage its use in general construction. The models can be used to evaluate the potential influence of adjusting mix variables on concrete properties required to ensure successful development of MS-SCC using PFA.

Table 1
Chemical and physical properties of PFA and cement

	PFA part 1	Cement
SiO_2	50	20.8
AL_2O_3	30	5
Fe_2O_3	7	3.2
CaO	2.3	63.7
MgO	1.2	2.6
K_2O	1.1	–
Na_2O	0.08	–
TiO_2	1.1	–
SO_3	0.4	–
CL	< 0.03	–
Free CaO	–	1.6
LOI	5.9	0.65
Na_2O eq.	–	0.39
Moisture content	NIL	–
Retained 45 μm (%)	5.8	
Water requirement (%)	94	
Strength factor at 28 days	0.85	
Bulk density	1.2–1.7 g/cm^2	
Compressive strength at 28 days (MPa)[a]	60.7	
Particle density (kg/m^3)	2029	–
Specific surface area (m^2/kg)	–	385

[a] BS 3892 Part 1: 1997.

Table 2
Grain size of coarse aggregate and sand

	Sieve size (mm)										
	28	20	14	10	5	2.5	1.25	0.63	0.31	0.16	0.075
20–5 mm	100	96	67	39	9.2	0	–	–	–	–	–
Sand	100	100	100	100	100	91	77	59	25	1.7	0

2. Material properties

The concrete mixes investigated in this study were prepared with Standard 42.5 N grade Portland cement and PFA. The cement and PFA used conformed to Standard BS ENV 197-1 CEM1 and Part 1:BS 3892. The chemical and physical properties of cement and PFA are presented in Table 1.

Continuously graded crushed basalt aggregate with a nominal particle size of 20 mm was used. Well-graded quartzite sand, with a fineness modulus of 2.74, was employed. The relative density values of the coarse aggregate and sand were 2.90 and 2.56, and their absorption rates were 0.8% and 1%, respectively. The grain-size distributions of the coarse aggregate and the sand are given in Table 2.

An SP based on chains of modified polycarboxylic ether was used and had 30% solid content and a specific gravity of 1.05.

3. Factorial experimental plan and test methods

3.1. Experimental plan

A 2^4-statistical experimental design (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 [14]. Given 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

Table 3
Range of the factorial values for the composite plan

Coded values	− 1.68	− 1	0	+ 1	+ 1.68
PFA (kg/m$^{3)}$	59	100	160	220	261
SP (%)	0.0	0.2	0.5	0.8	1
Cement (kg/m^3)	183	210	250	290	317
Water/Powder	0.38	0.45	0.55	0.65	0.72

Fig. 1. Orimet combined with JRing and JRing combined with cone.

modelled region, it is advisable to limit the use of the models to an area bound by coded 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 α value is 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 taken here as ± 1.68. Five 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 [15].

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 PFA content, SP dosage, cement content and W/P are defined. The modelled experimental region consisted of mixes ranging between the coded variables of -1.68 to $+1.68$ and is given in Table 3. The derived statistical models are valid for mixes with W/P ranging from 0.38 to 0.72, dosages of SP ranging from 0% to 1% by mass of powder, cement content ranging from 183 to 317 kg/m^3 and PFA content ranging from 59 to 261 kg/m^3. The mass of coarse aggregate was fixed for all mixes at 837 kg/m^3 to enhance the filling and passing abilities and the resistance to segregation. The SCC responses modelled were slump flow, loss of fluidity, Orimet time, V-funnel time, H_1 of L-box, L-box ratio, JRing + Orimet, yield stress, plastic viscosity, segregation resistance, and 7-, 28- and 90-day compressive strengths.

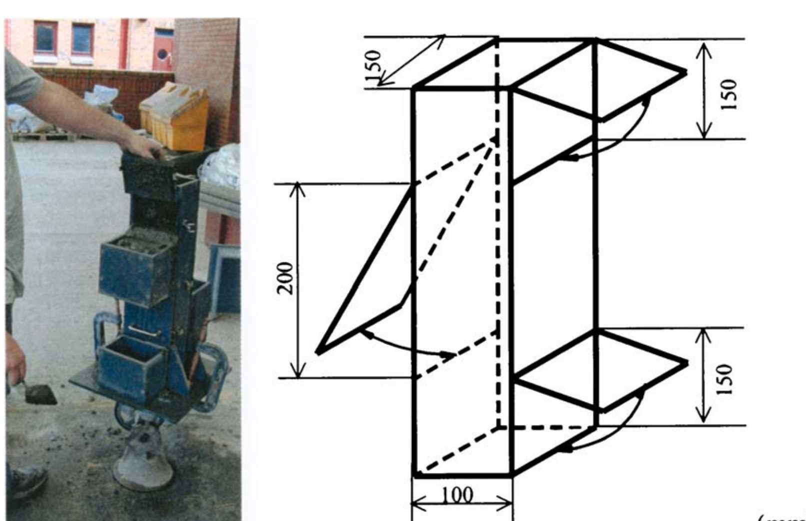

Fig. 2. Settlement segregation column apparatus.

Table 4
Mix proportions of all mixes used in the factorial design

Mix	Cement (kg/m^3)	PFA (kg/m^3)	W/B	SP (%)	Sand (kg/m^3)	Coarse aggregate (kg/m^3)
1	290	100	0.45	0.8	913	837
2	250	261	0.55	0.5	478	837
3	210	100	0.65	0.8	910	837
4	250	160	0.55	0.5	742	837
5	210	220	0.45	0.8	786	837
6	290	220	0.65	0.8	369	837
7	290	100	0.65	0.2	709	837
8	290	220	0.45	0.2	625	837
9	250	160	0.55	0.5	742	837
10	250	160	0.55	0.5	742	837
11	250	160	0.55	0.5	742	837
12	250	160	0.55	0.0	739	837
13	210	100	0.45	0.2	1066	837
14	317	160	0.55	0.5	594	837
15	250	29	0.55	0.5	1006	837
16	210	220	0.65	0.2	562	837
17	250	160	0.55	0.5	742	837
18	250	160	0.38	0.5	919	837
19	250	160	0.55	1.0	746	837
20	250	160	0.72	0.5	566	837
21	183	160	0.55	0.5	891	837

3.2. Test methods and mix proportions

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 s, 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 bags to minimise the evaporation of the mixing water and to let the dry aggregates in the mixer absorb the water. After 5 min, the cement and PFA were added and mixed for another minute. Finally, the SP was introduced, and the concrete was mixed for 3 min.

Slump flow, L-box [16], V-funnel and IBB concrete rheometer [17] were used to test the workability, passing ability and rheology 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 V-funnel [3] was used for the determination of the flow time of fresh concrete. The yield stress (G in Nm) and the plastic viscosity (H in Nm s) were determined using the IBB concrete rheometer. The test involves recording the torque required to maintain a four-finger impeller rotating in a planetary motion at an angular speed of 0 to 1.2 rps. The descending flow curve was used for the linear regression analysis. The Bingham model was adopted for concrete to evaluate the flow resistance and the viscosity factor [17]. In addition, new methods were introduced to test passing ability (blockage) and segregation, that is, the Orimet combined with the JRing and with the slump cone (Fig. 1), and the settlement column test (Fig. 2). The slump spread of SCC through the JRing was measured when the concrete stopped flowing (Fig. 1). The dimensions of the JRing were 300-mm diameter at its centreline and 100-mm height. The clear gap between the bars was 55 mm. The resistance to segregation was measured by the settlement column test [16,18,19], which is shown in Fig. 2. The dimensions used for the settlement column test are 500 × 150 × 100 mm. The test involves samples of concrete being taken from the top and bottom parts of a column-shaped

Table 5
Properties of fresh and hardened concretes used in factorial design

Mix	Slump flow (mm)	Fluidity loss (%)	Orimet time (s)	V-funnel (s)	H_1 (mm)	L-box ratio	JRing + Orimet (mm)	JRing + cone (mm)	Yield stress G (Nm)	Plastic viscosity H (Nm s)	Segregation ratio	7-day f'_c (MPa)	28-day f'_c (MPa)	90-day f'_c (MPa)
1	434	11.3	2.94	4.45	443	0.00	500	345	4.63	15.89	0.77	32.3	42.7	55.9
2	705	17.3	2.77	2.88	500	0.58	665	532	–	–	0.27	9.6	17.0	29.5
3	575	10.4	2.83	3.03	490	0.45	558	458	2.61	6.93	–	11.1	19.1	28.0
4	625	20.8	1.28	2.13	485	0.43	610	452	1.99	4.08	0.53	13.9	24.1	41.5
5	555	19.8	2.72	4.87	460	0.20	535	390	2.59	18.58	0.85	15.5	26.7	45.6
6	785	–	0.99	1.31	510	0.89	745	630	–	–	0.28	12.9	–	21.8
7	623	2.1	–	3.89	500	0.70	200	570	–	–	0.29	12.8	26.6	35.7
8	345	16.0	2.39	5.24	322	0.00	360	325	3.69	14.02	0.76	11.5	32.9	44.9
9	605	16.5	1.31	1.95	470	0.31	590	445	1.77	5.09	0.62	17.5	26.0	40.9
10	625	20.0	1.70	2.33	495	0.45	645	520	2.24	6.89	0.62	16.9	28.5	42.8
11	605	23.0	1.81	2.27	475	0.32	560	415	1.68	5.88	0.73	15.3	26.4	39.2
12	419	10.5	2.05	3.03	430	0.00	445	348	1.80	6.80	0.68	15.5	27.3	42.0
13	200	–	–	–	0	0.00	–	200	–	–	–	38.4	54.3	74.2
14	697	2.7	–	4.18	510	0.89	–	647	–	–	–	17.0	29.1	29.1
15	200	–	–	–	0	0.00	–	200	–	–	0.84	39.5	51.7	67.5
16	737	15.2	–	2.69	495	0.67	627	625	–	–	0.13	6.2	10.2	19.7
17	600	20.8	1.66	2.19	477	0.41	585	440	1.76	6.38	0.70	14.7	25.3	39.2
18	200	–	–	–	0	0.00	–	200	–	–	0.97	23.9	36.3	48.3
19	790	8.9	9.63	5.43	510	0.89	760	710	–	–	–	15.8	26.7	40.3
20	880	2.3	3.88	2.53	512	0.97	728	835	–	–	–	6.2	11.0	17.2
21	361	17.5	3.49	5.69	300	0.00	352	325	2.57	15.30	0.80	12.0	22.1	34.2

Table 6
Parameter estimates of all derived models

	Slump flow (mm)	Fluidity loss (%)	Orimet time (s)	V-funnel (s)	H_1 (mm)	L-box ratio	JRing + Orimet (mm)	Jring + cone (mm)	Yiel stress *G* (Nm)	Plastic viscosity *H* (Nm s)	Segregation ratio	7-day f'_c	28-day f'_c	90-day f'_c
R^2	.99	.99	.99	.99	.99	.99	.99	.87	.98	.98	.99	.99	.99	.99
Parameter	Estimate	Estimate	Estimate	Estimate	Estimate	Estimate	Estimate	Estimate	Estimate	Estimate	Estimate	Estimate	Estimate	Estimate
Intercept	605.2	20.2	1.55	2.17	480.4	0.35	597.50	462.7	1.89	5.66	0.64	15.8	26.1	40.1
PFA	105.4	− 8.8	5.13	− 1.85	91.3	− 0.81	75.9	70.0	− 1.42	− 4.33	0.31	− 4.5	− 5.7	− 5.8
SP	78.2	− 9.4	2.25	− 1.55	100.3	0.56	93.8	NS	− 0.96	− 3.45	NS	NS	NS	− 4.2
Cement	50.2	− 11.9	NS	− 0.45	29.7	NS	NS	54.1	− 0.40	− 5.73	0.37	NS	NS	NS
W/P	170.6	− 15.4	2.69	− 1.43	65.6	0.29	NS	153.0	− 1.41	− 10.16	− 0.29	− 7.7	− 12.7	− 17.3
PFA^2	− 48.9	− 4.1	− 2.62	− 0.68	31.8	NS	NS	NS	1.86	6.46	NS	3.0	2.9	3.5
SP^2	NS	− 3.7	1.52	0.73	NS	NS	NS	NS	− 0.60	NS	− 0.10	NS	NS	NS
$Cement^2$	NS	− 3.6	NS	0.98	− 26.7	0.16	− 109.8	NS	NS	NS	− 0.08	NS	NS	− 2.5
W/P^2	NS	− 6.7	− 0.78	0.98	− 79.3	0.047	NS	NS	NS	NS	NS	NS	NS	− 2.1
PFA × SP	NS	− 11.1	− 5.64	0.31	− 35.0	NS	NS	NS	NS	NS	NS	2.3	NS	3.6
PFA × Cement	NS	− 10.0	− 3.15	NS	− 72.0	− 0.57	NS	NS	NS	NS	− 0.14	NS	NS	NS
PFA × W/P	NS	− 10.0	NS	NS	− 40.5	0.57	77.3	NS	NS	NS	NS	4.9	NS	NS
PFA^3	NS	4.9	NS	1.21	− 47.1	0.35	NS	NS	NS	NS	− 0.17	− 1.54	NS	NS
SP^3	NS	3.2	NS	0.80	− 27.1	NS	NS	NS	NS	NS	− 0.12	NS	NS	NS
$Cement^3$	NS	2.7	NS	NS	11.6	NS	NS	NS	NS	NS	− 0.22	NS	NS	2.8
W/P^3	NS	5.7	NS	NS	30.6	NS	NS	NS	NS	NS	NS	NS	NS	NS

NS: nonsignificant

apparatus via doors after a controlled jolting cycle and standard settlement period. Those samples were analysed to determine the proportion of the coarse aggregate. Segregation resistance is expressed as the ratio between the coarse aggregate mass in the top part and the coarse aggregate mass in the bottom part. A lower ratio indicates more coarse aggregate in the bottom layer and, therefore, an increased tendency to segregation.

4. Test results and discussion

4.1. Derived models

The mix proportions and test results of 21 mixes prepared to derive the factorial design models are summarized in Tables 4 and 5, respectively. The results of the derived models prepared in this study, along with the correlation coefficients and the relative significance, are given in Table 6. The estimates for each parameter refer to the coefficients of the model found by a least-square method. The significance of each variable on a given response is evaluated using *t* test values based on Student's distribution. Probabilities less than .05 are often considered as significant evidence that the parameter is not zero; that is, the 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, fluidity loss, Orimet, V-funnel, H_1 (L-box), L-box ratio, JRing and Orimet, JRing and cone, yield value, plastic viscosity, segregation ratio, and 7-, 28- and 90-day f_c' were found to be .99, .99, .99, .99, .99, .99, .99, .87, .98, .98, .99, .99, .99 and .99, respectively. The high correlation coefficient of most responses demonstrates excellent correlation, where it can be considered that at least 95% of the measured values can be accounted for with the proposed models.

The variables in Table 6, in coded values, present the comparison of various parameters as well as the interactions of the modelled responses. A negative estimate signifies that an increase of the given parameter results in a reduction of the measured response. For any given response, the presence of parameters with coupled terms, such as PFA PFA and PFA^3, indicates that the influence of this parameter (PFA) is quadratic and cubic.

Table 7 shows the average, standard deviation and coefficient of variation (COV), as well as the standard errors and the relative errors, with 95% confidence limit of measured response of the five repeated mixes: slump flow, loss of fluidity, Orimet time, V-funnel, H_1 (L-box), L-box ratio, JRing + Orimet, JRing + cone, yield stress, plastic viscosity, segregation ratio, and 7-, 28- and 90-day f_c'. The relative errors at the 95% confidence limit for slump flow, V-funnel, H_1 (L-box), JRing + Orimet, JRing + cone, and 7-, 28- and 90-day f_c' are shown to be limited to 2% to 10%. On the other hand, the relative errors for fluidity loss, Orimet time, L-box ratio, yield stress and segregation ratio ranged approximately between 12% and 16%, while that of plastic viscosity was 20%.

4.2. Accuracy of the proposed models

The accuracy of each of the proposed models was determined by comparing predicted-to-measured values obtained with mixes prepared at the centre of the experimental domain and five other mixes. The predicted-to-measured values for slump flow, plastic viscosity, Orimet, V-funnel, H_1 (L-box), JRing + Orimet, JRing + cone, segregation ratio, 7- and 28-day f_c' are shown in Figs. 3 and 4, with the estimated errors corresponding to a 95% confidence limit (dotted lines). The estimated errors for slump flow, fluidity loss, Orimet, V-funnel, H_1 (L-box), L-box ratio JRing + Orimet, JRing + cone, yield value, plastic viscosity and segregation ratio were ± 11mm, ± 2.3%, ± 0.23 s, ± 0.14 s, ± 9 mm, ± 0.057, ± 30 mm, ± 37 mm, 0.22 Nm, ± 1 Nm s and 0.08, respectively. This value was ± 1.5 MPa for compressive strength at 7, 28 and 90 days.

The ratios between the predicted and the various measured properties of MS-SCC (five central points and five simulated mixes) slump flow, fluidity loss, Orimet, V-funnel, H_1 (L-box), L-box ratio, JRing + Orimet, JRing + -

Table 7
Repeatability of test parameters

	Initial slump flow (mm)	Fluidity loss (%)	Orimet time (s)	V-funnel time (s)	H_1 L-box	L-box ratio	JRing-Orimet (mm)
Mean ($n=5$)	612	20.2	1.55	2.17	480	0.38	598
Standard deviation	12	2.4	0.24	0.15	9.8	0.06	31.7
COV %	2.0	11.7	15.5	6.7	2.0	16.8	5.3
Estimated error at 95%	11.4	2.3	0.23	0.14	9.3	0.057	30.2
	JRing-cone (mm)	**Yield stress *G* (Nm)**	**Plastic viscosity *H* (Nm s)**	**Segregation ratio**	**7-day f_c' (MPa)**	**28-day f_c' (MPa)**	**90-day f_c' (MPa)**
Mean ($n=5$)	454	1.89	5.66	0.64	15.7	26.1	40.7
Standard deviation	39.2	0.23	1.1	0.08	1.5	1.6	1.6
COV %	8.0	12.0	19.5	12.2	9.6	6.2	3.8
Estimated and relative errors at 95%	37.4	0.22	1.0	0.08	1.4	1.5	1.5

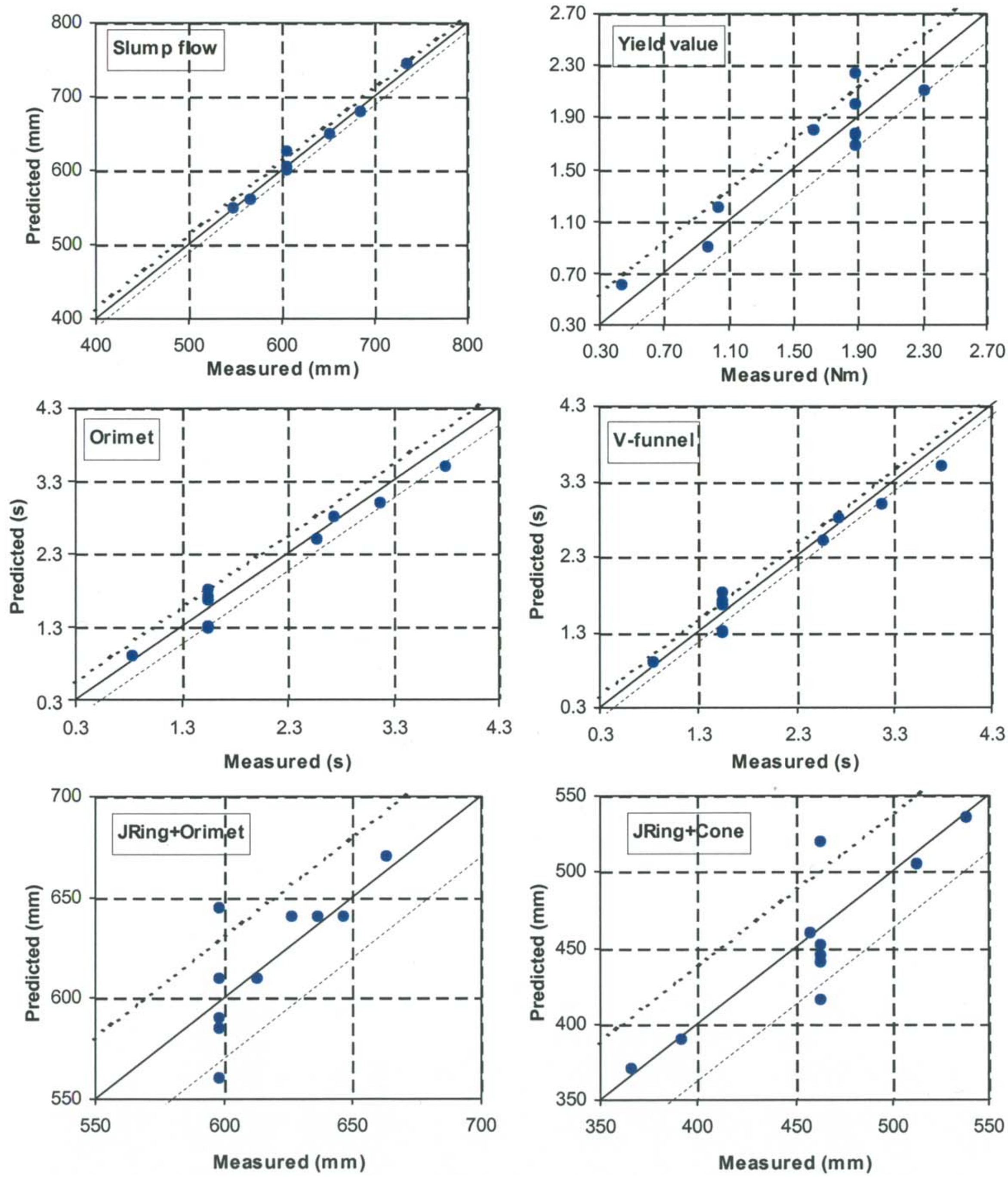

Fig. 3. Examples of measured properties versus predicted from statistical models of slump flow, yield value, Orimet, V-funnel, JRing + Orimet and JRing + cone.

cone, yield stress, plastic viscosity, segregation ratio, and the compressive strength at 7, 28 and 90 days were 0.99, 1.0, 1.02, 1.0, 1.01, 0.92, 1.00, 1.02, 0.99, 0.98, 1.01, 1.01, 1.01 and 0.99, respectively. The ratio of predicted-to-measured values ranged between 0.98 and 1.01, thus indicating good accuracy for the established models to predict the filling ability, passing ability, segregation and compressive strength, except for the L-box ratio (predicted-to-measured = 0.92). In general, the proposed models appear to be satisfactory in predicting the flowability, passing ability, segregation resistance and strength, with low scattering between the measured and predicted values.

4.3. Exploitation of statistical models using response surface methods

Derived mathematical models are useful tools in understanding the effect of various mix constituents and their interactions on MS-SCC properties. The analysis of the derived models enables the identification of major trends

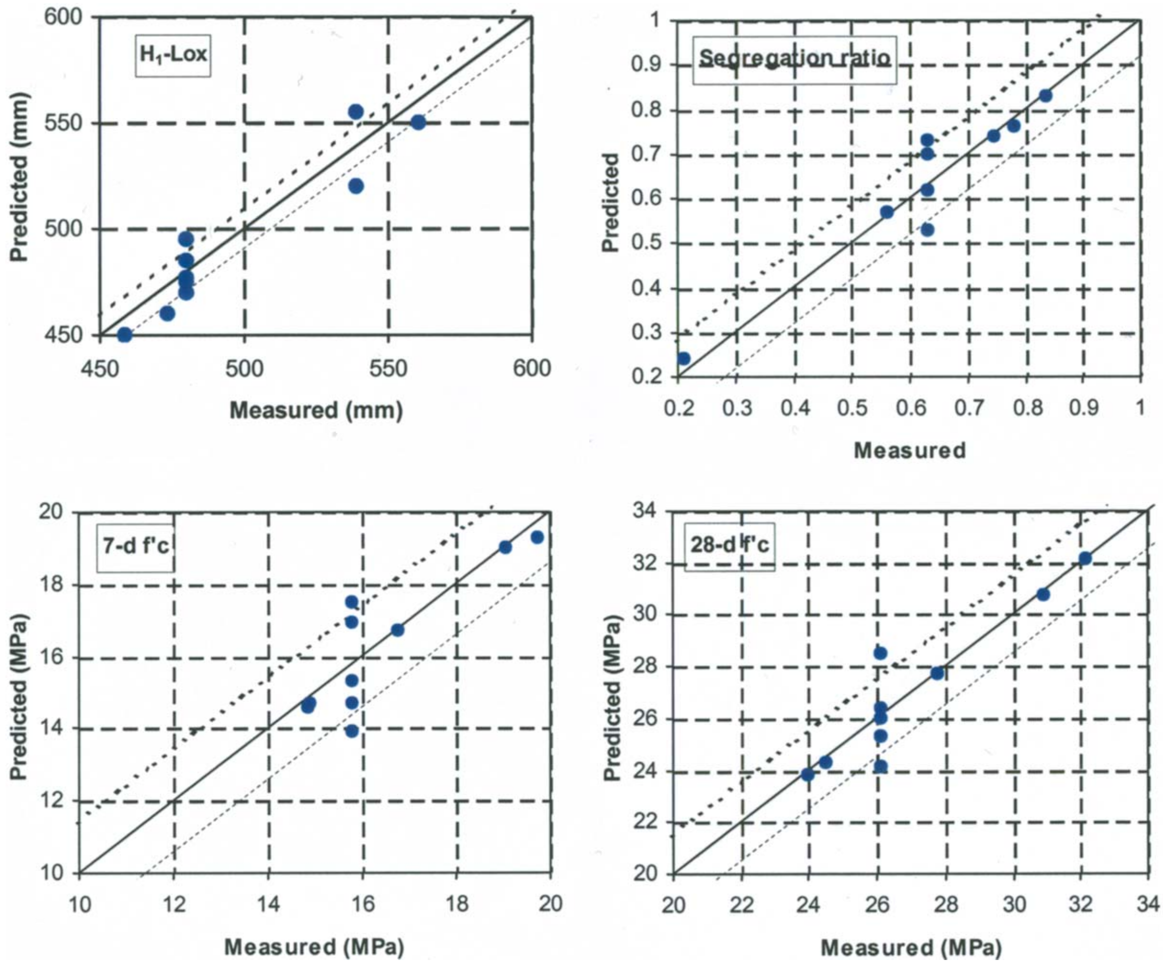

Fig. 4. Examples of measured properties versus predicted from statistical models of H_1 (L-box), segregation ratio, and 7- and 28-day f'_c.

and predicts the most promising direction for future mix optimisation. This can reduce the cost, time and effort associated with the selection of trial batches. It is important to note that the factorial design approach used in this study can be applied easily to other materials to make mixes that modify the existing models.

The application of such models to assist in the selection of mixes is illustrated with the following examples: slump

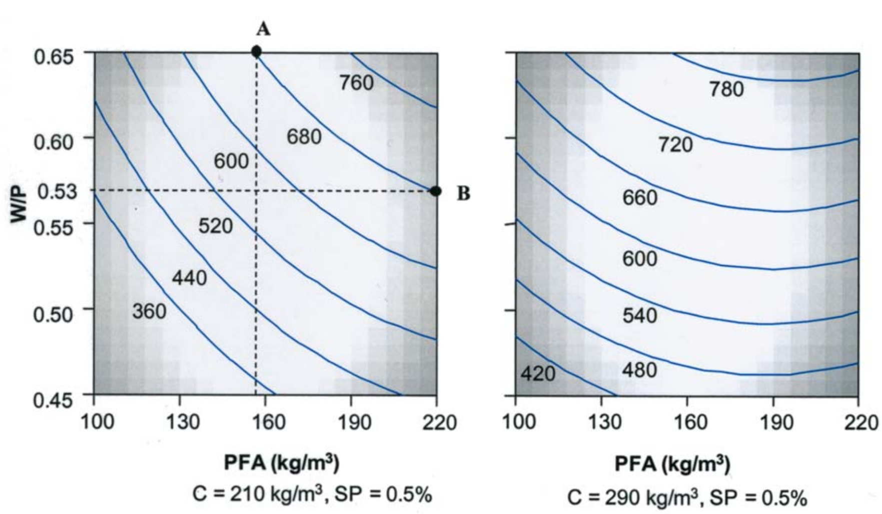

Fig. 5. Isocurves of slump flow versus W/P and PFA of mixes made with 210 and 290 kg/m^3 of cement and 0.5% SP.

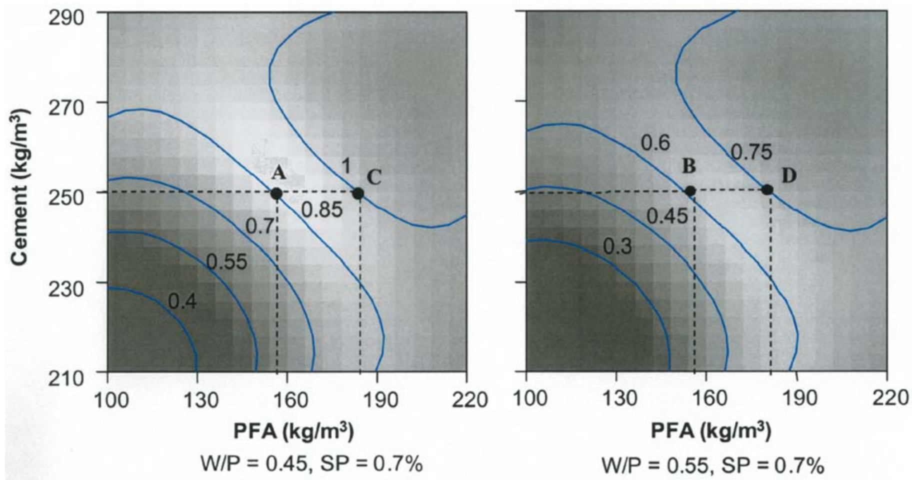

Fig. 6. Isocurves of segregation ratio versus cement and PFA contents of mixes made with 0.7% SP, and 0.45 and 0.55 W/P.

flow, segregation ratio and compressive strength. As shown in Table 6, the slump flow is influenced by, in significant order, W/P, dosage of PFA, dosage of SP, cement content and then other interaction effects. The W/P had the greatest effect on the slump flow (170.6). The increase in dosage of PFA had two times greater effect than an increase in cement content (+105.4 vs. +50.2). However, the increase in W/P had approximately 3 and 2.2 times greater influence on increasing slump flow than the increase in cement content and the dosage of SP, respectively (+170.6 vs. +50.1 and +78.2).

For example, the effect of increasing W/P on slump flow versus the dosage of PFA, when dosages of SP and cement were fixed at 0.5% and 210 and 290 kg/m^3, respectively, is shown in Fig. 5. The increase in PFA dosage for a given value of cement led to an increase in slump flow. Note also that an increase in cement content from 210 to 290 kg/m^3, for any given value of PFA, enhanced fluidity. With the dosages of SP and cement fixed at 0.5% and 210 kg/m^3, respectively, and to maintain slump flow of 680 mm from point A to B (Fig. 5), the decrease in W/P (0.65 to 0.53) necessitates an increase in the dosage of PFA (155 to 220 kg/m^3).

The influence of cement and PFA contents on segregation ratio for mixes made, with fixed SP of 0.7% and 0.45 and 0.55 W/P, are plotted in Fig. 6. The contour diagrams of Fig. 6 indicate that the increase in cement and PFA contents (for a given SP and W/P) enhances the resistance to segregation (increase segregation ratio). However, for a given SP dosage, the increase in W/P from 0.45 to 0.55 reduces the segregation ratio. For example, SCC made with W/B of 0.45 and cement and PFA contents of 250 and 155 kg/m^3, respectively, can exhibit a drop in segregation ratio from 0.85 (Point A) to 0.60 (Point B) when W/P is increased from 0.45 to 0.55 (Fig. 6). For a similar increase of W/P, such reduction can be 1 (Point C) to 0.75 (Point D) for SCC made with 250 and 185 kg/m^3 of cement and PFA, respectively (Fig. 6).

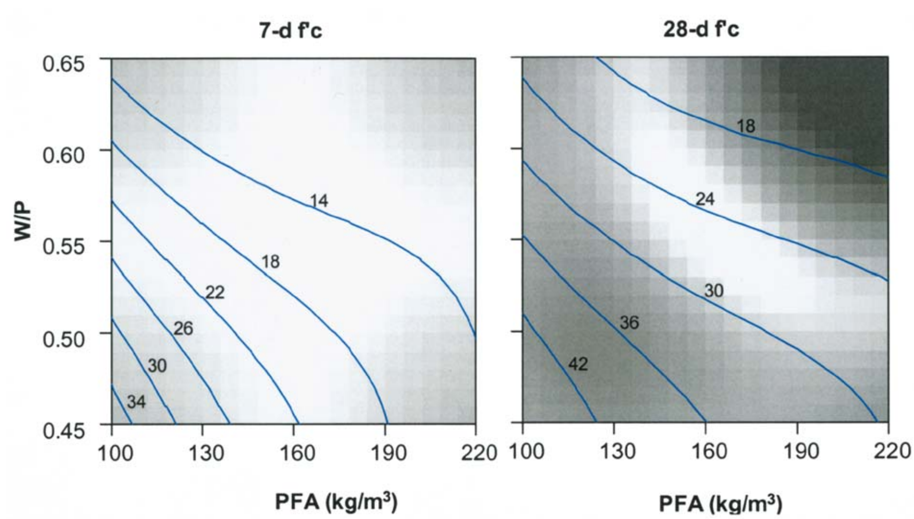

Fig. 7. Isocurves of 7- and 28-day f'_c versus W/P and PFA (Cement = 250 kg/m^3, SP = 0.5%).

Fig. 7 shows the isocurves of the variation of the compressive strength at 7 and 28 days with the cement and PFA contents. As expected, the W/P had the greatest effect on the compressive strength at 7 and 28 days, followed by the PFA content. However, the dosage of SP showed no significant effect on the compressive strength. For any given W/P, the increase of PFA content led to a decrease in the compressive strength at 7 and 28 days. For example, 35 MPa of compressive strength at 28 days can be achieved with a mix having W/P of 0.51 and containing 135 kg/m^3 of PFA and 250 kg/m^3 of cement and 0.5% SP.

5. Conclusions

The effects of the content of cement and pulverised fuel ash, W/P, the concentration of SP on the filling ability, rheological properties, passing ability, segregation and compressive strength were investigated. The proposed statistical models can simplify the test protocol required to optimise a given mix SCC by reducing the number of trial batches needed to achieve a balance among mix variables. This is due to the use of the models in conducting simulations of various variables to secure successful filling ability, passing ability, resistance to segregation and medium compressive strength. The models established using factorial design approach are valid for a wide range of mix proportioning and provide an efficient means to determine the influence of key variables on MS-SCC properties. These models can also provide relationships between the foregoing results for mix optimization and quality control. The modelling and prediction of the response of other points in the experimental domain were therefore possible. Although the models are based on a given set of materials, they can be easily used to generate future results using other materials.

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