A STUDY OF STATISTICAL MODELS APPLICATION FOR MIXTURE OF HIGH-FLOWING CONCRETE

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Li, Ming-Chih; Chen, Yu-Sheng; Chan, Yin-Wen; and Hoang, Vihn Long (2012) "A STUDY OF STATISTICAL MODELS APPLICATION FOR MIXTURE OF HIGH-FLOWING CONCRETE," *Journal of Marine Science and Technology*: Vol. 20: Iss. 3, Article 12.
DOI: 10.51400/2709-6998.1811
Available at: https://jmstt.ntou.edu.tw/journal/vol20/iss3/12

A STUDY OF STATISTICAL MODELS APPLICATION FOR MIXTURE OF HIGH-FLOWING CONCRETE

Ming-Chih Li, Yu-Sheng Chen, Yin-Wen Chan, and Vihn Long Hoang

ABSTRACT

High flowing concrete (HFC) is defined as a concrete that exhibits a high deformability and a good resistance to segregation. The grade of workability for HFC is concrete slump flow that between 50 to 70 cm. In the research, 21statistically balanced concrete mixtures were investigated by statistical models, and discussed further the workability, strength and durability properties of concrete, which are responded by granulated ground blastfurnace slag (GGBS), Fly ash, water-binder ratio (w/b) and superplasticizer (sp). The Box-Wilson central composite design (CCD) method is used in this study. The total binder content is 375 kg/m^3, and four independent variables such as percentage of GGBS as cement replacement (20 to 50% by mass), percentage of Fly ash as cement replacement (15 to 35% by mass), w/b (0.39 to 0.45) and percentage of SP (1.0 to 1.4 by binder mass) are used for the design of HFC mixtures. The fresh properties of mortar and concrete, mechanical properties and durability characteristics of concrete are measured. Finally, the concrete slump flow model, T_{50}, 7-, 28- and 90-day compressive strength model, the RCP (rapid chloride permeability) model, and Carbonation model are developed successfully. The proposed response models of HFC offer useful information regarding the mixture optimization.

I. INTRODUCTION

Concrete is the most important element of the infrastructure today and well-designed concrete can be a multi-functional material. However, the production of cement brings many harmful gases such as CO_2, NO_2, and SO_2. It is an important subject to reduce the cement content of concrete. The traditional concrete is one kind of uneconomic concrete that with high water to cement ratio and low workability is difficult to place, and some problems are easy to occur, like honeycomb and bleeding. To solve these problems, concretes with high workability and high durability, such as self-compacting concrete have recently been developed and applied. SCC is a special type of concrete with great self-compacting ability that can fill the formwork and vacancy among rebars without the need of vibration or compacting during the process of concrete placement. The multi-advantages of SCC had been produced with a high dosage of powder, as well as a high dosage of superplasticizer and well-graded aggregates. However, such concrete needs to increase more cost and cement content. Some problems such as the actual strength is much higher than the design strength and heat of hydration need be considered. It is uneconomical to use the SCC in general construction. Thus the HFC that developed with using industrial by-products such as Fly ash and GGBS to reduce the cement content of concrete has advantages in general construction.

HFC is a special type concrete with high slump flowing and high resistance to segregation. The workability index of HFC is slump flow, and the range of slump flow has been considered between 50 and 70 cm [1]. The difference between traditional concrete and HFC are high slump and high slump flow, the HFC was different from SCC that needed to be vibrated while placing. The high flowability can easily be achieved by adding performance sp to the concrete, the more dosage of sp, the more slump flow. Reduction in viscosity and shear yield stress, which leads to increase the workability of concrete. On the other hand, it is a way to improve the workability of concrete by adjusting water to binder ratio, adding to mineral admixture such as GGBS and Fly ash. The stability will be reduced with the increase of flowability result in increased risk of coarse segregation, whether dynamic segregation or stable segregation. To enhance its stability so that the paste can maintain the coarse aggregates in uniform suspension, higher powder content is required [18]. An easy way to avoid segregation on chemical admixture addition is to increase the sand content by 4 to 5% at the cost of coarse aggregate [19]. To enhance the viscosity of mortar lead to decreased risk of coarse segregation by reducing the lubrication and friction between paste and fine aggregate. An alternative approach is

to incorporate a viscosity-modifying admixture (VMA) to enhance the segregation resistance [6]. VMA is one kind of water-soluble polymer that can absorb free water in the fresh concrete result in enhancing viscosity of concrete. This research is aimed at developing HFC with low cement content. The workability can be arrived with using pozzolanic material replacement for cement, increasing the S/A and adjusting the sp. Furthermore, long term for mechanics properties and durability ability can be improved by adding pozzaolanic material replacement. Thus the influence of GGBS, Fly ash, sp and w/b on rheology, mechanical properties and durability ability of HFC which is important and the researches are required. For this purpose, the statistical method will be used to design to concrete mixtures variables and the analysis of experiment result.

The Response surface methodology (RSM) consists of a set of statistical methods that can be used to develop improvement or optimize products that had been used to investigate the fresh and harden properties of concrete mixtures in recent years [15, 21]. A factorial design was carried out to mathematically model the influence of four key parameters, including the content of cement, pulverized fuel ash, water to powder ratio and dosage of SP on filling and passing abilities, segregation and compressive strength. Finally, the medium strength self-compacting concrete incorporating pulverized fuel ash was developed successfully [22]. The minimum use of water-reducing admixtures and to optimize use of Fly ash in SCC was investigated and the high-volume Fly ash SCC was successfully developed [15]. Four independent variables such as total binder content (350 to 450 kg/cm^3), percentage of Fly ash as cement replacement (30 to 60% by mass), percentage of high-range water-reducing admixtures (0.1 to 0.6% by solid mass), and water-binder ratio w/b (0.33 to 0.45) were sued for the design of SCC mixtures. The fresh concrete properties were determined from slump flow , V-funnel flow, filling capacity, bleeding, air content, and segregation tests. The mechanical properties and durability ability of SCC such as compressive strength, rapid chloride permeability, freezing-and-thawing resistance, and drying shrinkage were determined to evaluate the performance of SCC. The statistical models to predict workability, compressive strength and the rapid chloride permeability of SCC were developed and their performances were validated. Thus, the influence of multi-parameter on concrete such as fresh and harden properties can be analyzed by suing statistical treatment of experimental results. In this research, the statistical method was carried out to discuss the influence of GGBS as cement replacement, Fly ash as cement replacement, water to binder ratio and the dosage of chemical admixture on workability, compressive strength and durability properties of concrete.

II. EXPERIMENTAL PLAN

1. Materials

As for the materials used in this study, TYPE I Ordinary

Table 1. Chemical composition of cement, GGBS and Fly ash.

	SiO$_2$	Al$_2$O$_3$	CaO	MgO	Fe$_2$O$_3$	Finess (cm^2/g)	Loss on ignition (%)
cement	20.89	5.61	63.87	2.93	3.13	3520	-
GGBS	35	8.9	39	7.2	0.23	4100	-
Fly ash	46	25.55	1.44	0.56	4.63	-	5.1%

Table 2. Physical properties of aggregates.

Type	Fine aggregate	Coarse aggregate
Specific gravity	2.62	2.63
Fineness modulus	2.71	6.61
Absorption (%)	1.3	0.8

Portland Cement (OPC), granulated ground blastfurnace slag (GGBS) with normal fineness, and F type Fly ash were used. The chemical compositions of OPC, GGBS, and Fly ash are shown in Table 1. Continuously graded gravel with a nominal particle size of 20 mm was used. Natural river sand with F.M of 2.71 is used as fine aggregate. Table 2 presents the basic physical properties of fine and coarse aggregate.

2. Statistical Model and Mixture Design

The Box-Wilson central composite design (CCD) method was used to design of mixture variables in this study. Four input factors were used in the test program such as X1 (percentage of GGBS as cement replacement by mass), X2 (percentage of Fly ash as cement replacement by mass), X3 (water to binder ratio), and X4 (percentage of SP as a percentage of mass of binder). The ranges of the input factors were set at 10 to 50% for X1, 5 to 35% for X2, 0.44 to 0.50 for X3, and 0.9 to 1.3% to X4. The CCD method consists of three portions: the fraction factorial portion, the center portion, and the axial portion. The interaction between two variables was presented by the fraction factorial portion and the axial portion allows the estimation of curvature. To repeat experiments for the central portion that is useful to estimate experiment error are needed.

The number of runs for fraction factorial portion was decided by 2k-1, where k (= 4 in this study) is the number of factors. The total number of mixtures for fraction factorial portion was kept at $2^{4-1} = 8$ with a different combination of coded value varying between +1 and -1 as shown in Table 3. The number of runs for axial portion was set 2k = 8 for the experimental program. The coded value of portion is set at $F^{1/4} = 8^{1/4} = 1.68$, where F is the number of runs in fraction factorial portion of the design. The center point portion are needed to get good estimation of pure experimental error. According to Schmidt and Launsby [20], the minimum number of center point can be obtained form $4 \times (F + 1)^{1/2} - 2k$. A total of five runs (mixtures) was kept for the center point

Table 3. Limit and coded value of factors (variables).

Factor	Range	Coded value				
		-1.68	-1	0	+1	+1.68
X1	10 to 50%	10	18	30	42	50
X2	5 to 35%	5	11	20	29	35
X3	0.39 to 0.45	0.39	0.40	0.42	0.44	0.45
X4	1.0 to 1.4%	1	1.08	1.2	1.32	1.4
CCD portion	Mixture	factors				
		X1		X2		X3		X4
Fractions factorial	6,8,10,11,13,17,20,21	±1		±1		±1		±1
Center point	1,2,9,15,18	0		0		0		0
Axial	3,4,5,7,12,14,16,19	0, ±1.68		0, ±1.68		0, ±1.68		0, ±1.68

Table 4. Mixture proportions of HFC (binder = 375 kg/m^3).

Mixture no.	Cement kg/m^3	X1, GGBS		X2, Fly ash		X3 w/b	X4 sp, %	Water kg/m^3	Aggregate kg/m^3	
		%	kg/m^3	%	kg/m^3				Coarse	fine
1	187.5	0.30	112.5	0.20	75.0	0.47	1.10	176	798	940
2	187.5	0.30	112.5	0.20	75.0	0.47	1.10	176	798	940
3	131.3	0.30	112.5	0.35	131.3	0.47	1.10	176	775	940
4	262.5	0.10	37.5	0.20	75.0	0.47	1.10	176	804	940
5	187.5	0.30	112.5	0.20	75.0	0.50	1.10	188	768	940
6	109	0.42	157.1	0.29	108.5	0.45	0.98	170	799	940
7	112.5	0.50	187.5	0.20	75.0	0.47	1.10	176	793	940
8	266	0.18	67.9	0.11	41.5	0.45	0.98	170	833	940
9	187.5	0.30	112.5	0.20	75.0	0.47	1.10	176	798	940
10	266	0.18	67.9	0.11	41.5	0.45	1.22	170	833	940
11	176	0.42	157.1	0.11	41.5	0.49	1.22	183	791	940
12	243.8	0.30	112.5	0.05	18.8	0.47	1.10	176	822	940
13	199	0.18	67.9	0.29	108.5	0.49	0.98	183	770	940
14	187.5	0.30	112.5	0.20	75.0	0.47	1.30	176	798	940
15	187.5	0.30	112.5	0.20	75.0	0.47	1.10	176	798	940
16	187.5	0.30	112.5	0.20	75.0	0.47	0.90	176	798	940
17	109	0.42	157.1	0.29	108.5	0.45	1.22	170	799	940
18	187.5	0.30	112.5	0.20	75.0	0.47	1.10	176	798	940
19	187.5	0.30	112.5	0.20	75.0	0.44	1.10	165	828	940
20	199	0.18	67.9	0.29	108.5	0.49	1.22	183	770	940
21	176	0.42	157.1	0.11	41.5	0.49	0.98	183	791	940

portion with '0' coded value. The final coded value is set at five different levels such as -1.68, -1, 0, +1, and +1.68 as shown in Table 3. The mixture proportions of 21 HFC mixtures are presented in Table 4. The amount of fine aggregate was kept constant at 940 kg/m^3 while the quantity of coarse aggregate varied as the mixture design procedure was based on absolute volume method.

3. Preparation and Casting of Test Specimens for HFC

All concrete mixtures were prepared in 70-l batches in a horizontal axis concrete mixer. After the mixing, the fresh concrete tests such as slump flow test, T_{50} test and air content test were conducted. From each batch, nine 10×20 cm cylinders for compressive strength, three 10×20 cm cylinders for rapid chloride permeability test, three 10×20 cm cylinders for carbonation test were cast. All HFC specimens were cast that divided into three layers with hand compaction 5 times per layer. After casting, all the specimens were covered with plastic sheets and water-saturated burlap, and left at room temperature for 24 h. The specimens were demolded and transferred to the moist-curing room maintained at 23°C and 100% relative humidity until testing.

4. Tests on Fresh Properties of HFC

The flowability and workability of HFC were conducted by slump flow and T_{50} that the time of slump flow to reach a diameter 500 mm (T_{50}). The T_{50} test of concrete performed in accordance with ASTM C1611 [2]. For the slump flow, the spread diameters were measured for the average of two measurements at right angles to each other, and were recorded to the nearest 10 mm. The slump flow also was carried out by ASTM C1611 [2]. As chong Hu [7] supposes, the slump value over 8 cm and without heavy segregation behaves as a Bingham material in the steady state. Slump flow of concrete was control by shear yield stress and viscosity. The slump flowing was not observed until the shear stress yield decreased lower than inward shear stress of concrete. The lower shear yield stress of fresh concrete results in the higher slump. HFC is one kind of concrete of large slump and high flow, including lower shear yield stress. Moreover, the fluid rate of flow of HFC was affected by viscosity of mortar. It is the important role played by the viscosity of HFC in considering segregation resistance. Thus, T_{50} in our study is regarded as an index of viscosity. The air content was determined according to ASTM C231 [3].

5. Compressive Strength and Durability of HFC

Concrete compressive strength was determined according to ASTM C39 [4] for concrete samples. The compressive strength was measured for 7, 28, and 90 days. The average compressive strength of three 100×200 mm cylinders was considered for each age. The rapid chloride permeability (RCPT) test is fully described in ASTM C 1202 [5] at an age of 90 days. Samples were prepared by cutting and discarding 25 mm slices from the top of 100×200 mm cylinders, and the remaining section cut into 50 mm-thick specimens and prepared as per ASTM C 1202 [5]. Each specimen was the placed between two cells filled with 0.3 N NaOH and 3.0% NaCl solutions. The total charge in coulombs passed in 6h through the 50 mm-thick specimens was considered as the resistance of the specimen to chloride ion penetration. An accelerated carbonation test was performed according to the method designed by Papadakis *et al.* [14] and the carbonation depth was determined with phenolphthalein test by RILEM CPC-18 [16]. Phenolphthalein is mixed as a solution of 1% in 70% ethyl alcohol. Before spraying, the surface of concrete needed to been cleaned. Phenolphthalein is a basic-base indicator that turns colorless in acidic solutions and pink in basic solutions when the pH is above a value of 9.5. The carbonation depth can be measured on the colorless zone.

III. RESULTS AND DISCUSSION

1. Fresh Properties

Test results of slump flow, T_{50}, and air content are presented in Table 5. All of the concrete mixtures except mixtures 5, 6, 7, 8, 11, 16, and 19 are qualified as HFC because the exhibited satisfactory slump flow between 50 and 70 cm. The segrega-

tions were not observed among mixtures 7, 11, and 14 that slump-flow were slightly larger than 70 cm. Mixture 5, which had a slight segregation and exhibited a large slump flow of 73.5 cm. The coarse segregation, including dynamic segregation and stability segregation can be controlled by viscosity of concrete. The degree of viscosity was estimated to the time of T_{50} or the v-funnel time. The targets of T_{50} and V-funnel time are proposed to SCC about 3 to 15 s and 7 to 20 s (JSCE 1998) [10]. The T_{50} of mixtures 6, 8, 16, and 19 were not recorded as the slump flow of concrete was not reaching 500 mm to measure. All other mixtures exhibited excellent T_{50} between 3.2 to 12.6 s. On the other hand, all of mixtures were exhibited an air content of lower than 4%.

2. Compressive Strength and Durability

The compressive strengths for different water to binder ratio and different quantities of pozzolanic materials as cement replacement of concrete specimens at the age of 7, 28, and 90 days are presented in Table 5. For 7-day strengths were between 180 to 340 kgf/cm^2 and incorporating pozzolanic materials in concretre decreases the compressive strength from 334 to 181 and from 216 to 180 kgf/cm^2, respectively such as mixture 12, 3, 4, and 7. For 28-day compressive strengths of all HFC were between 280 and 470 kgf/cm^2. Quite a few pozzolanic effect of GGBS in concrete was observed, which the compressive strength of mixture 1 approximated to mixture 4 even though the addition of GGBS more than mixture 4. For 90-day compressive strength of all HFC were between 390 and 570 kgf/cm^2, all concrete mixtures strengths more than 7 to 45% of 28-day strengths. It show that the compressive strength were still increasing by pozzolanic effect in a long term. The results are consistent with another observation, which the activity of Fly ash much lower than GGSB.

The durability of the HFC, the rapid chloride permeability test (RCPT) and the carbonation test were carried out. All of the concrete mixtures except mixtures 5 and 12 appeared to be very low (ASTM C1202) [5] and ranged between 435 and 1120 coulombs of all mixtures in Table5. The influences of the charge passed are the amount of pozzolanic materials such as GGBS and Fly ash and water to binder ratio in this study. The total charge passed decreases with an increase of percentage of GGBS and Fly ash as cement replacement and a decrease of water to binder ratio. The results show that incorporates pozzolanic materials in HFC has a lower chloride ion penetration. The carbonation of HFC, the carbonation depth increase with increasing the percentage of pozzolanic materials as cement replacement and water to binder ratio, and the water to binder affects carbonation seriously.

3. Development of Statistical Models

An empirical statistical model was thought to be a useful design tool to optimize the mixture of concrete. The statistical model was used to optimize self-consolidating concrete with limestone [11, 8]. In the study, the results of experiments such as the concrete fresh properties, compressive strength, and

Table 5. Properties of fresh concretes, compressive strengths, and durability ability.

No.	Workability properties			Compressive Strength			Durability properties		
	Slump flow (cm)	T_{50} (sec)	Air content (%)	7-day (kgf/cm^2)	28-day (kgf/cm^2)	90-day (kgf/cm^2)	RCP		Carbonation
							Coulombs (C)	Rating	Depth (mm)
1	67	6.53	3.2	255.4	381.1	475	644	Very low	10.4
2	66	7.02	2.9	251.2	393.5	465	620	Very low	10.9
3	68.5	7.56	3.2	181.1	304.4	415	493	Very low	18.3
4	58	9.31	3.2	261.1	385.2	433	937	Very low	7.6
5	73.5	3.22	2.9	218.6	321.8	389	1019	Low	13.3
6	38	Nr	2.1	213.9	316.0	437	510	Very low	13.8
7	71	4.22	2.8	186.3	325.8	403	620	Very low	17.8
8	33	Nr	2.1	322.4	460.3	569	759	Very low	8.3
9	69	6.82	2.7	248.3	374.7	471	654	Very low	11.1
10	63	12.63	2.3	309.6	415.5	538	813	Very low	8.4
11	72	4.34	2.8	252.2	367.2	437	879	Very low	12.3
12	64	6.25	2.4	334.4	414.8	483	1120	Low	6.1
13	56	5.97	2.8	240.0	312.6	423	813	Very low	13.5
14	72	6	2.4	251.7	395.3	483	530	Very low	10.0
15	65	6.43	3.0	263.4	387.5	461	680	Very low	10.2
16	44.5	Nr	2.2	300.8	427.2	457	629	Very low	9.6
17	69	6.35	2.7	193.0	289.0	419	451	Very low	14.0
18	67	6.44	3.3	243.6	375.6	481	678	Very low	10.5
19	42	Nr	2.4	317.1	470.4	572	435	Very low	5.9
20	69	4.01	3.4	194.2	289.9	400	828	Very low	14.0
21	57.5	7.66	3.4	223.8	344.8	425	814	Very low	11.3

Nr: not recorded.

durability properties were analyzed with the statistical method to set up the slump flow model, T_{50} model, compressive strength models, RCP model, and carbonation model. The STATA statistical software was used to derive several models by least square approach. The statistical models can be used to evaluate the influences of the BBGS as cement replacement, the Fly ash as cement replacement, water to binder ratio, and SP on the workability, the compressive strength, and the durability.

In addition, the statistical inference based by OLS will be invalid when ignoring the potential problem of heteroskedasticity. This paper checks whether the estimated variance of the residuals in the estimation regression are same by using Breusch-Pagan test [9, 23]. The paper weights the standard error of estimators of OLS by using Heteroskedasticity-robust standard error proposed by White (1980) to find the valid inference when the sample that we are considered displays the non-constant error variance. Two-level fractional factorial design for four independent variables was used in the study. The basic model is as follow Eq. (1) and the parameters of the derived models are given in Table 6. The *p*-values of parameters estimated within the statistical model are required less than 5%, implying that the probabilities of error decisions with hypotheses, which the estimations of coefficients are large the given value, are less than 5%. In terms of model

selection, the seven major models are chose by comparing the values of the square of the correlation coefficient (R^2).

$$Y = cons + \alpha_1 sc + \alpha_2 fc + \alpha_3 wb + \alpha_4 sp + \alpha_{11} sc^2 + \alpha_{22} fc^2$$
$$+ \alpha_{33} wb^2 + \alpha_{44} sp^2 + \alpha_{12} scfc + \alpha_{13} scwb + \alpha_{14} scsp$$
$$+ \alpha_{23} fcwb + \alpha_{24} fcsp + \alpha_{34} wbsp$$

Here, sc = GGBS/cement

fc = Fly ash/cement

wb: water-binder ratio

sp: chemical admixture (%)   (1)

In the seven selected model, including Slump Flow, T_{50}, 7-d strength, 28-d strength, 90-d strength, RCP, Carbonation, statistical values of the Breusch-Pagan test for checking the variances with heteroskedasticity are, respectively, 5.93 (*p*-value = 0.0149), 3.42 (*p*-value = 0.0642), 0.06 (*p*-value = 0.801), 0.01 (*p*-value = 0.937), 1.36(*p*-value = 0.2444), 0.7 (*p*-value = 0.4022), 0.33 (*p*-value = 0.56), 5.93 (*p*-value = 0.0149).

The statistical values of Slump Flow and T_{50} models are statistically significant at least the 10%, implying that these two models have the problems with non-constant variances of

Table 6. Parameter estimates of al derived models.

	Slump flow (cm)	T_{50} (cm)	7-day f'c	28-day f'c	90-day f'c	RCP (C)	Carbonaion
R-squared	0.9841	0.9945	0.9324	0.9315	0.9498	0.9691	0.9717
Adjusted R-squared	0.9646	0.9909	0.9034	0.9087	0.9283	0.9485	0.9595
F-value	75.23	197.01	32.18	40.8	44.15	47.03	79.97
Prob > F	0	0	0	0	0		0
const.	-3918.52	5778.682	310.6529	1757.961	2545.29	-5404.14	36.05242
α_1	NS	-142.317	1318.169	NS	NS	4256.165	-94.795
α_2	-448.707	NS	NS	NS	-1481.67	-1661.14	-151.577
α_3	13017.15	-18116.5	NS	-2770.49	-4437.22	NS	NS
α_4	1533.442	-2371.67	NS	-77.0082	NS	5850.351	NS
α_{11}	-24.8926	NS	-42.9032	-62.2786	-71.5745	297.1863	NS
α_{22}	-33.0688	NS	NS	-127.543	NS	1011.15	NS
α_{33}	-11458.5	14388.57	NS	NS	NS	16463.95	-135.024
α_{44}	-245.315	295.9917	NS	NS	NS	-2684.4	NS
α_{12}	56.96969	5.426913	NS	NS	NS	NS	7.281582
α_{13}	49.39012	290.0101	-3273.24	222.7686	NS	-10313.6	201.0092
α_{14}	NS	NS	256.2982	358.664	111.4937	NS	NS
α_{23}	943.0059	NS	873.0213	NS	3419.652	NS	336.3375
α_{24}	NS	NS	-529.087	NS	-190.886	NS	NS
α_{34}	-1938.65	3515.038	NS	NS	NS	NS	NS

NS: nonsignificant.

the residuals in the estimation regressions. The paper further adjusts the variance of standard error in the Slump Flow and T_{50} model by using Heteroskedasticity-robust standard error proposed by White (1980). The empirical results of seven models are respected in Fig. 5. According to the index of R2, the overall extent of explanation in these seven models are, respectively, 0.984, 0.995, 0.932, 0.932, 0.950, 0.969, and 0.972, implying that the variables that we are considered in the models can account for 90% of the variance in the left-side variables. Moreover, statistical values of the test for the whole model (F-value) are significant at the 1% level, reflecting that our model have, in some extent, considerable explanations.

Slump Flow Models of HFC:

The HFC was defined by Architectural Institute of Japan that slump flow was between 50 and 70 cm and no segregation to occur in fresh concrete. The flowing ability was affected by a lot of variables such as the combination of binder, water to binder ratio, the dosage of sp, fine aggregate to total aggregate, and fineness modulus (FM) of sand. The composites of binder, water to binder ratio, and dosage of sp were considered in the research and the statistical method was used to set up slump flow model for the effective analysis. The proposed slump flow model is as follows:

$$\text{Slump Flow} = \text{cons} + \alpha_2 fc + \alpha_3 wb + \alpha_4 sp + \alpha_{12} scfc$$
$$+ \alpha_{13} scwb + \alpha_{23} fcwb + \alpha_{34} wbsp$$
$$+ \alpha_{11} sc^2 + \alpha_{22} fc^2 \alpha_{33} wb^2 + \alpha_{44} sp^2 \quad (2)$$

A typical response chart for the slump flow with a binder content 375 kg/m^3, 30% replacement of cement with GGBS, 20% replacement of cement with Fly ash is illustrated in Fig. 1. At given binder content and percentage of GGBS and Fly ash replacement as cement, desired slump flow can be predicted for different combinations of w/b and chemical admixture. Fig. 2 shows the influence of percentage of GGBS replacement as cement on slump flow of HFC. At given binder content, the 20% of Fly ash replacement as cement, and w/b = 0.47, increasing the percentage of GGBS replacement as cement can increase the slump flow substantially at any chemical admixture content. For example the slump flow is in 100mm increment with an increase from 20% to 40% in GGBS replacement. The Fig. 3 show that the influence of Fly ash replacement on slump flow. The proportion of the binder content, the w/b, and the GGBS replacement are maintained at 375 kg/m^3, 0.47, and 30% respectively, increasing the Fly ash replacement can increase the slump flow at any sp content. The slump flow can be increased about 5 cm while the Fly ash is in 20% increment. The Figs. 4 and 5 present a feasibility result that the slump flow can be maintained by using GGBS and Fly ash to reduce the dosage of sp. As can be seen from Fig. 4, the slump flow is maintained 600mm with increasing 20% GGBS replacement to reduce 0.08% by weigh of binder of the sp. The similar behavior can be observed in the Fig. 5, which the dosage of sp can be reduce 0.004% with the 20% increment of Fly ash to main the slump flow of 60 cm.
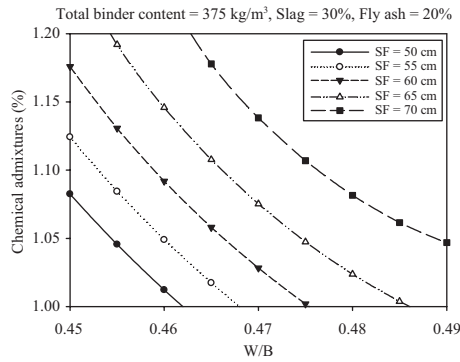
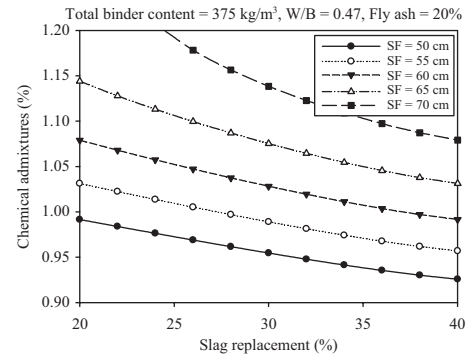Fig. 1. Typical response chart for prediction of slump flow.

Fig. 2. Influence of GGBS replacement on slump flow.

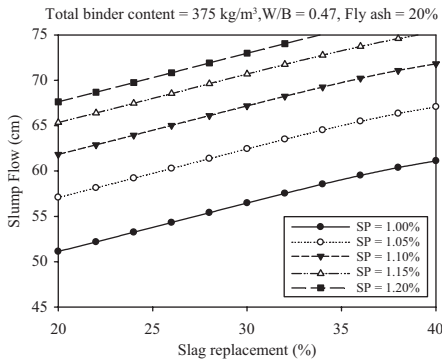

Fig. 3. Influence of Fly ash replacement on slump flow.

Fig. 4. Influence of BBGS on chemical admixture demand.
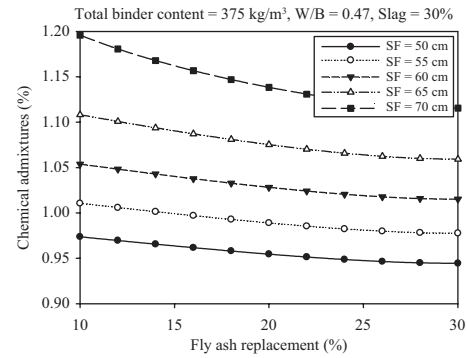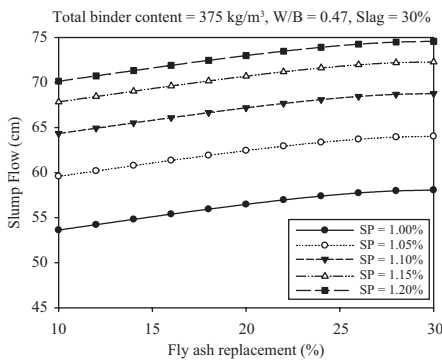

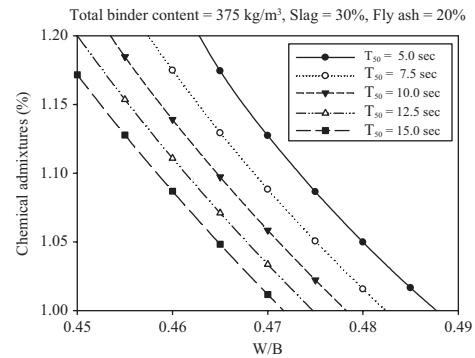Fig. 5. Influence of Fly ash on chemical admixture demand.

Fig. 6. Typical response chart for prediction of T_{50}.

T_{50} Model of HFC:

The time of slump flow to reach a diameter 50 cm can be considered to evaluation of the plastic viscosity of concrete. The more time of T_{50} the higher viscosity, the higher viscosity can maintain the stable of HFC without segregation. The target of T_{50} is proposed to SCC about 3 to 15 s. In the research, the T_{50} of all concrete mixtures except the mixtures that can't reach a diameter 500 mm are between 3 and 15 s. The derived statistical model of T_{50} is given in Eq. (3). A chart was presented to predict the T_{50} of HFC is shown in Fig. 6. At given binder content, GGBS replacement and Fly ash re-

placement, the T_{50} can be predicted for different combinations or w/b and sp. The T_{50} can be decreased while the w/b and the dosage of sp are increased. The Fig. 7 presented the influence of T_{50} on GGBS replacement and sp, which the increment of GGBS replacement and the sp result in reducing the T_{50} of HFC. Moreover, the T_{50} is affected by sp is larger than GGBS replacement.

At given w/b = 0.47, 30% and 20% Fly ash replacement, the T_{50} can be reduced 2 s with an increase 30% in GGBS replacement. The influence of T_{50} on Fly ash replacement under different dosage of sp were shown in Fig. 8 at given w/b = 0.47 and 30% GGBS replacement. A tendency can be
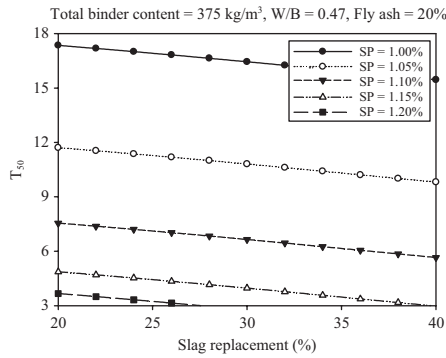
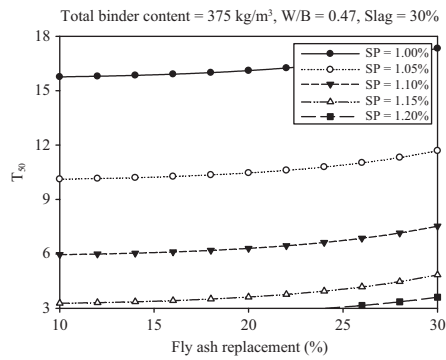Fig. 7. **Influence of GGBS replacement on T_{50}.**

Fig. 8. **Influence of Fly ash replacement on T_{50}.**

(a) Relation between GGBS and w/b

(b) Relation between Fly ash and w/b

Fig. 9. **Typical response chart for prediction of 28-day compressive strengths.**

observed in Fig. 8, which T_{50} can be increased with the increment of Fly ash replacement. It points out that the viscosity can be increased with Fly ash. From the above results, the responses of T_{50} were affected by w/b and sp are larger than GGBS and Fly ash replacement, and the T_{50} of HFC can be designed with the combination of the four variables.

$$T_{50} = cons + \alpha_1 sc + \alpha_3 wb + \alpha_4 sp + \alpha_{12} scfc + \alpha_{13} scwb$$
$$+ \alpha_{34} wbsp + \alpha_{33} wb^2 + \alpha_{44} sp^2 \qquad (3)$$

Compressive Strength Models of HFC:

The compressive strength is affected by many variables, including the w/b, the sp, the aggregate combination, and the binder combination, which the binder combination is much complicated. In the research, the 7-day, 28-day, and 90-day compressive strength models were derived by statistical analysis and the proposed models as follows:
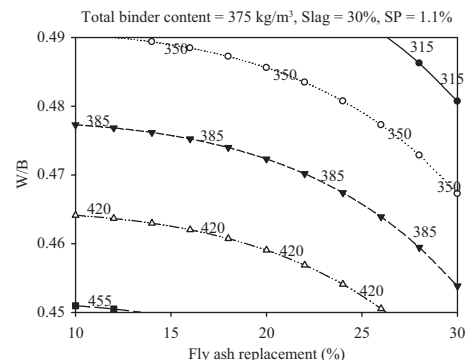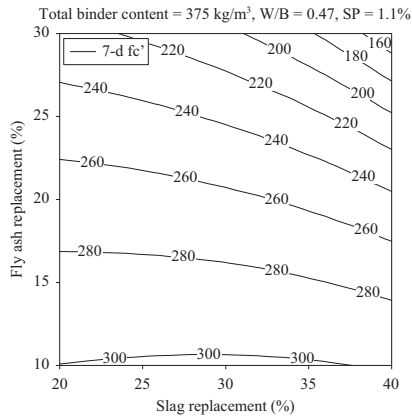
$$fc'7 = cons + \alpha_1 sc + scwb + scsp + \alpha_{23} fcwb + \alpha_{24} fcsp + \alpha_{11} sc^2 \qquad (4)$$

$$fc'28 = cons + \alpha_3 wb + \alpha_4 sp + \alpha_{13} scwb + \alpha_{11} sc^2 + \alpha_{22} fc^2 \qquad (5)$$

$$fc'90 = cons + \alpha_2 fc + \alpha_3 wb + \alpha_{14} scsp + \alpha_{23} fcwb + \alpha_{24} fcsp + \alpha_{11} sc^2 \qquad (6)$$

The response charts for 28-day compressive strength are developed and illustrated in Fig. 9. The Fig. 9(a) represented that the relation between GGBS replacement and w/b at given 20% Fly ash replacement and 1.1% sp. It is feasible to maintain the same compressive strengths by combination with GGBS replacement and w/b. As can be seen from Fig. 9(a), the compressive strength is maintained 350 kgf/cm² with reducing the w/b 0.04 to increase 20% GGBS replacement. The similar tendency is observed in Fig. 9(b), the compressive strengths can be maintained with combination with Fly ash and w/b.
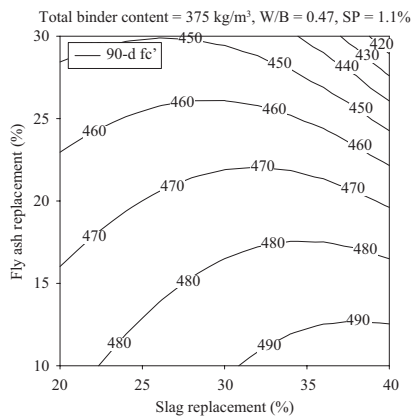
Fig. 10 shows the isocurves of the variation of the compressive strength at 7, 28, and 90 days with the different replacement of GGBS and Fly ash, which contains w/b = 0.47 and sp = 1.1%. Fig. 10(a) shows that the increase of GGBS and Fly ash replacement led to a decrease in the compressive strength at 7 day. It can be found that some combination of GGBS and Fly ash replacement increase 28-day compressive strength. For example, the highest compressive strength is found in the below right rather than in the below left of the Fig. 10(b). The same result is found in the Fig. 10(c), the highest compressive strength is in the below right. From the above results, the highest compressive strength moves to the below right from the below left follow the time in the Figs. 10(a), 10(b), and 10(c). The phenomenon is resulted from pozzolanic effect of GGBS and Fly ash, and the

Total binder content = 375 kg/m³, W/B = 0.47, SP = 1.1%

(a) Isocurve of 7-day fc'

Total binder content = 375 kg/m³, W/B = 0.47, SP = 1.1%

(b) Isocurve of 28-day fc'

Total binder content = 375 kg/m³, W/B = 0.47, SP = 1.1%
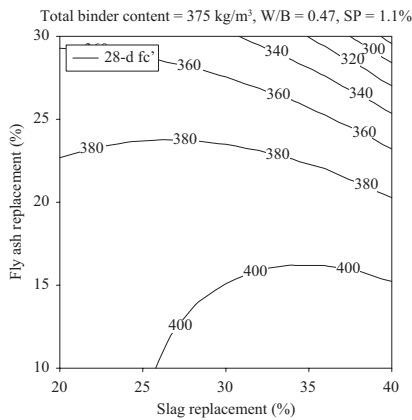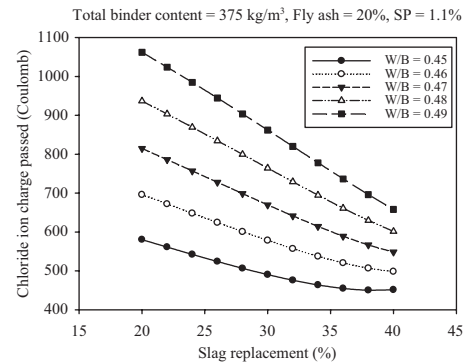

(c) Isocurve of 90-day fc'

Fig. 10. Influence of GGBS and Fly ash replacement on 7-day, 28-day, and 90-day compressive strength.

Total binder content = 375 kg/m³, Fly ash = 20%, SP = 1.1%

(a) Influence of GGBS and w/b on RCP

Total binder content = 375 kg/m³, Slag = 30%, SP = 1.1%

(b) Influence of Fly ash and w/b on RCP

Total Binder cement = 375 kg/m³, W/B = 0.47, SP = 1.1%

(c) Influence of GGBS and Fly ash on RCP

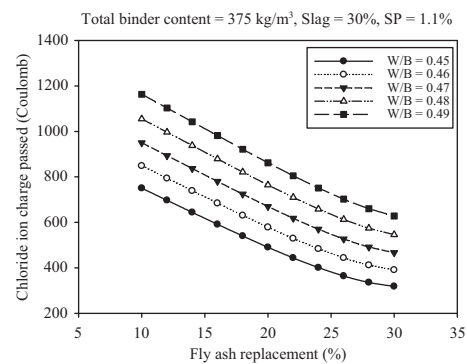**Fig. 11. Influence of multi-parameters on RCP.**

pozzolanic effect of GGBS is better than Fly ash. As can be seen from Fig. 10, the HFC mixture design can be optimized with the combination of GGBS and Fly ash replacement.
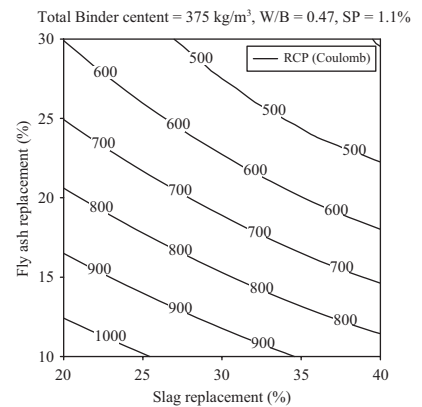
The RCP Model of HFC:

The basic factors influencing the reinforcing steel corrosion are the oxygen, the water, and the chloride. The chloride plays a major role in the corrosion of reinforcing bars. The corrosion behavior of steel bars induced by internal chlorides in concrete and can result in the deterioration of concrete [18]. In the research, the RCP model was developed to evaluate the ability of resistance to chloride ion penetration of the HFC with the w/b, GGBS replacement, and Fly ash replacement. The RCP model is given in Eq. (7). The Fig. 11 shows that the influence of four parameters on the resistance to chloride ion penetration. The charts can be observed that the ability of resistance to chloride ion penetration increases significantly by reducing the w/b. At the same time, it can be found the similar effect on the pozzolanic material. At given w/b = 0.47 and the 20% Fly ash as cement replacement, the charge passed

can be reduced from 800 to 550 coulombs with an increase from 20 to 40% in GGBS replacement. Furthermore, the charge passed can be reduced from 950 to 460 with a 20% increment or the Fly ash, while the w/b = 0.47 and the 30% GGBS as cement replacement were given. The influence of GGBS and Fly ah replacement on the RCP, with fixed w/b = 0.47 and sp = 1.1%, are observed in Fig. 11(c). As the diagram indicates, the total charge passed is below 500 coulombs while the GGBS and Fly ash replacements are more than the 60% of total binder content.

$$\mathbf{RCP} = cons + \alpha_1 sc + \alpha_2 fc + \alpha_4 sp + \alpha_{13} scwb + \alpha_{11} sc^2 + \alpha_{22} fc^2$$

$$+ \alpha_{33} wb^2 + \alpha_{44} sp^2 \tag{7}$$

The Carbonation Model of HFC:

The primary factors influencing carbonation rate are the diffusivity/permeability, the reserve alkalinity, the environmental carbon dioxide concentration, and the exposure condition [12]. The greater carbonation resistance derived from the lower permeability can reduce the inward diffusion of carbon dioxide into the concrete. The permeability of concrete is affected by w/b, the pore structure of concrete, and the timely curing. The lower permeability and greater carbonation resistance concrete can be obtained from reducing w/b, and improving pore structure with pozzolanic materials. On the other hand, the reserve alkalinity is considered to resist the carbonation. The reserve alkalinity is from calcium hydroxide that arises from cement, and the more cement content the more calcium hydroxide to against carbon dioxide. On the contrary, the more replacement as cement of GGBS and Fly ash result in lower reserve alkalinity. The w/b, the pozzolanic material, and the dosage of sp were considered in the study, for a given the carbon dioxide concentration and the exposure condition. The carbonation of HFC is as follows:

$$\mathbf{Carbonation} = cons + \alpha_1 sc + \alpha_2 fc + \alpha_{12} scfc + \alpha_{13} scwb$$

$$+ \alpha_{23} fcwb + \alpha_{33} wb^2 \tag{8}$$

The response charts for the carbonation depth are developed and illustrated in Fig. 12. As the increment of GGBS replacement, there is a slight increase of carbonation depth with low w/b, there is, however, a steep rise of carbonation depth with high w/b, which can be observed in Fig. 12(a). At the same time, the similar phenomenon is represented in the Fig. 12(b). This is a manifestation of the increment of the w/b and pozzolanic materials content affect the carbonation rate significantly. This is no disagreement on this point that the increment of w/b result in raising pores and capillary porosity in the concrete, which is expected to increase the permeability. On the other hand, the GGBS and Fly ash as cement replacement are used to impact the capillary porosity of the paste and reducing the permeability of concrete. However, it needs to be considered that the more replacement of GGBS
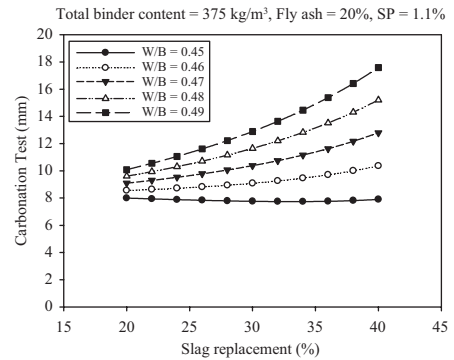
(a) Influence of GGBS and w/b on carbonation
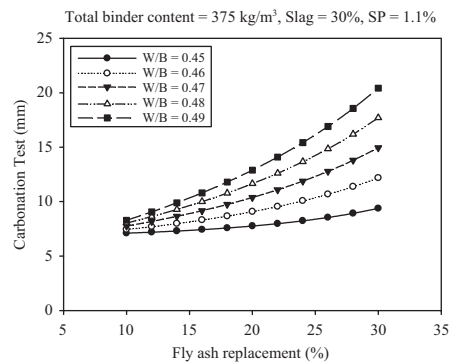
(b) Influence of Fly ash and w/b on carbonation
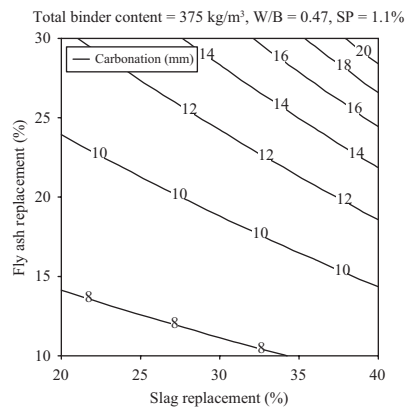
(c) Influence of GGBS and Fly ash on carbonation

Fig. 12. Influence of multi-parameters on carbonation.

and Fly ash the lower reserve alkalinity to resistance to the carbon dioxide. As mentioned above, for a given w/b = 0.47 and sp = 1.1%, the largest carbonation is found in the above right in the Fig. 12(c).

IV. CONCLUSIONS

In this research, 21 special concrete mixtures are used to probe into the influence of GGBS as cement replacement, Fly ash as cement replacement, w/b, sp on concrete fresh properties, compressive strength, and durability properties. The range of variables that we considers, the binder contain 375

kg/m^3, GGBS as cement replacement from 10 to 50%, Fly ash as cement replacement from 5 to 35%, w/b between 0.44 and 0.50, and sp between 0.9 and 1.1%. Slump flow of mixtures to conform to the requirement of HFC (slump flow between 50 and 70 cm), the 28-day compressive strength are between 289~415 kgf/cm^2. It seems reasonable to conclude that the medium strength HFC can be development successfully with low binder contain (375 kg/m^3) by suing proportional replacement cement with pozzolanic materials.

With the scope of this study, following conclusions can be drawn.

1. The four selected variables of GGBS replacement percentage, Fly ash replacement percentage, w/b, and sp percentage that present positive influence on the HFC, including fresh properties, strength, and durability by statistical analysis of the experiment data.
2. GGBS and Fly ash have capability to reduce the dosage of sp to achieve the same slump flow. The dosage of sp can be reduced with increment of GGBS and Fly ash as cement replacement for a constant slump flow. At given w/b and sp content, increasing GGBS and Fly ash replacement can increase the slump flow.
3. The w/b and sp have a greater influence on the viscosity, which T_{50} decreases with the increment of w/b and sp content. On the other hand, For a given w/b and sp, the more GGBS replacement increases, the more T_{50} decreases and the more Fly ash replacement increases, the more T_{50} increases.
4. In the mechanical property, 7-day, 28-day, and 90-day compressive strength models were developed successfully to analyze the influence of four variables on compressive strength. In addition to this, the zones of pozzolanic effect were show in the isocurve of 90-day compressive strength.
5. In the durability of HFC, the charge passed was affected by w/b, GGBs replacement, and Fly ash. The increment of w/b led to increase the charge passed and increase concrete permeability. However, the charge passed can be reduced by increment of GGBS and Fly ash as cement replacement. It is important that the increment of Fly ash as cement replacement is benefic more than reducing the w/b to improve concrete permeability with containing the slump flow.
6. For the carbonation of HFC, the larger w/b led to high permeability, thereby resulting in lower carbonation resistance. On the other hand, The more pozzolanic material as cement replacement to decrease the reserve alkalinity, result in lower ability to resist the carbonation. It needs to be noted that the increase of GGBS and Fly ash replacement is more negative effects in terms of carbonation rate at high w/b.
7. This is a reasonable way to optimize mixtures of medium strength HFC by suing fresh properties, strength, and durability models to cut down the cost, improve workability with maintaining the compressive strength and the durability.

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