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Optimization of Self-Consolidating Concrete Containing Metakaolin Using Statistical Models

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Abstract: This paper uses the statistical design of experiments method to optimize the mixture design for self-consolidating concrete (SCC) incorporating metakaolin. Factors (variables) studied were total binder content, percentage of metakaolin in the mixture, water-to-binder ratio, and curing conditions. The range of the chosen factors was determined using the central composite design (CCD) of experiments method. A total of 20 mixtures were tested at both the fresh state and after a curing period of 28 days. The fresh, hardened, and durability performance of the SCC mixtures were compared based on two sets of tests. The first set of tests was implemented to evaluate the fresh properties of the mixture including slump flow, V-funnel, L-box, J-ring, and air content tests. The second set of tests involved compressive strength and rapid chloride permeability tests (RCPT) at 28 days. Two curing regimes were used for each statistical model for comparison including air and water curing. The results obtained from the developed CCD models were exploited to determine the most significant factors affecting the properties of SCC and the optimum level of each variable.

1. Introduction

Self-consolidating concrete (SCC) is a class of concrete with high flow ability which achieves compaction under its self-weight without the use of vibrators. This flow ability can be attained by adding high range water reducer admixtures (HRWRA) and/or incorporating supplementary cementing materials (SCM). Different SCM's have been successfully used for the production of SCC, such as fly ash, silica fume, and slag (Lachemi et al. 2003). Metakaolin is a relatively new SCM; it has been widely used for the production of high strength and performance concrete over the past two decades. In the recent years, metakaolin was introduced for the production of SCC. The behavior of metakaolin in SCC mixtures was found to be similar to that in normal concrete mixtures which enhances the overall mechanical and durability performance (Hassan et al. 2012).

Statistical design of experiments is a useful tool to benchmark the optimum mixture components of SCC. Additionally, prediction models can be developed to evaluate the response at different levels of the governing factors. By using such models, the numerical optimization can then be performed to minimize or maximize the response. For example, Ghezal et al. (2002) utilized statistical factorial design methods to optimize SCC containing limestone filler. The resulting prediction models were successfully employed in the selection of SCC mixture proportions that can maintain high strength at a relatively low cost. Another study conducted by Sonebi (2004) examined the use of statistical analysis for SCC mixture design. In his research, the statistical models were applied to optimize the mixture proportions of SCC containing pulverized fuel ash. Different variables were studied including the content of cement and pulverized fuel ash, water-powder ratio, and the dosage of the HRWRA. The models tested the filling ability, passing ability, segregation, compressive strength, and cost of SCC mixtures. The results of optimization yielded the desired levels of each ingredient of a medium strength SCC with minimum costs.

However, when SCC is used for structures in severe environments, such as offshore structures, the durability of SCC is considered the most critical design aspect. These structures are deteriorating at an increasing rate owing to the corrosion of embedded steel. It has been proven that chloride permeability of concrete is the most significant factor influencing the corrosion of steel. As a result, for the complete optimization of SCC, additional prediction models are required to evaluate the durability of SCC in terms of chloride permeability.

Hassan et al. (2012) investigated the effect of using metakaolin and silica fume on the durability of SCC. The replacement level of cement by metakaolin and silica fume varied, but water-to-binder ratio and total binder content remained constant. They concluded that the use of metakaolin increased the viscosity, passing ability, compressive strength and durability of SCC when compared to silica fume. In addition, the optimum replacement level for metakaolin and silica fume was found to be 20% and 8%, respectively. It is not clear in their investigation, however, if the total binder content had an effect on the rheology, strength, and durability of SCC containing metakaolin.

In another study, Patel et al. (2004) developed statistical models to predict the behavior of SCC containing high volumes of fly ash. These models included the fresh, hardened, and durability performance of SCC mixtures. Their target was to exploit the statistical models to minimize the amount of the HRWRA, and maximize the strength and durability of SCC. The factors examined were total binder content, percentage of fly ash, percentage of HRWRA, and water-to-binder ratio. Their results showed a valuable exploitation of the statistical methods to optimize SCC mixtures.

On the other hand, the use of different pozzolanic materials was compared by applying the central composite design (CCD) of experiments method (Dogan et al. 2009). Their comparison was based on the chloride permeability of normal vibrated concretes containing fly ash, granulated blast-furnace slag, and silica fume. A rapid chloride penetration test (RCPT) was performed to examine the chloride permeability of such concretes both for air curing and water curing conditions. The results showed that the use of CCD method was an appropriate technique for the design and optimization of concrete regarding the RCPT.

The purpose of this paper is to design and optimize SCC mixtures containing metakaolin with respect to fresh, mechanical, and durability characteristics. For this reason, similar statistical models were produced to investigate the effects of total binder content, water-to-binder ratio, and percentage of metakaolin replacement. Two curing techniques were also adopted, including air and water curing for a period of 28 days, to study the effect of curing on the compressive strength and chloride permeability of SCC. The significance of this study is to design an SCC mixture that can achieve the balance between flow ability and durability. The results obtained from this investigation are of special interest for engineers considering the use of metakaolin in the production of high strength and high performance SCC.

2. Experimental Program

A total of 20 SCC mixtures were designed by applying the Box-Wilson central composite design (CCD) method (Schmidt et al. 1994). Three factors varied throughout the 20 mixtures including total binder content (A = 400-500 kg/m^3), water-to-binder ratio (B = 0.35-0.45), and percentage of metakaolin replacement of cement (C = 0-25%). The coarse-to-fine aggregate ratio (0.9) was kept constant for all the mixtures. The amount of HRWRA was determined based on maintaining a required slump flow of approximately 650 ± 50 mm (as per ASTM C1611). Upon achieving this slump value, the first set of fresh properties tests was implemented. The tests included time to reach 500 mm diameter (T_{500}) with the slump flow, J-ring flow diameter, T_{500} with J-ring, air content tests (based on ASTM C1611; C1621; C231, respectively), V-funnel, and L-box tests (according to The European Guidelines for Self-Compacting Concrete, 2005). These tests examine the flowing ability (slump flow), viscosity (T_{500} and V-funnel), passing ability (J-ring and L-box), filling ability (L-box), segregation (V-funnel), and air content of each SCC mixture.

After completing the tests for the fresh properties, (100 mm diameter x 200 mm height) cylinders were casted and cured for a period of 28 days for testing the compressive strength and rapid chloride permeability. Two curing regimes were used; the first regime was to submerge the samples in water for 28 days, while the second regime was to store them in air for the whole 28 days period. Both regimes were performed at a controlled temperature of about 23° C. After the completion of the curing period, the compressive strength and rapid chloride permeability tests were performed on both air- and water-cured samples according to the standard tests ASTM C39; and C1202, respectively. Next, a statistical analysis was performed on the results from each test and prediction models for each test response were developed. The statistical analysis was completed by commercially available software for the design and analysis of experiments. Finally, using these models, the optimum level of each factor was determined. In addition, the optimum SCC mixture was tested for validating the prediction models by comparing the results obtained from the models and the actual tests.

2.1 Materials

In this program, type GU Canadian Portland cement similar to ASTM Type I, with a specific gravity of 3.15, was used for the 21 (including one validation mixture) SCC mixtures. The metakaolin present in this research was delivered Eastern United States by Advanced Cement Technologies, conforming to ASTM C618 Class N, with a specific gravity of 2.56. Natural sand and 10 mm maximum size stone were included as fine and coarse aggregates, respectively. The coarse and fine aggregates each had a specific gravity of 2.70 and water absorption of 1%. A high range water reducer admixture (HRWRA), similar to ASTM Type F (ASTM C494), was applied to control the slump flow diameter of SCC mixtures.

2.2 Mixtures Design and SCC Proportions

The design of mixtures was obtained after determining the different levels of each factor by using the CCD method. This method divides the design space into three parts: the full-factorial part, the axial part, and the central part (Schmidt et al. 1994). The three parts together yielded the 20 runs which were represented by 20 SCC mixtures included in the study. The three parts consist of examining the studied factors at five different levels by the criteria shown in Table 1. The first part, the full-factorial, involved studying the three factors or variables ($k = 3$) at two levels only (–1 and +1 in coded factors) with a total number of runs of $n_f = 2^k = 8$ runs. Secondly, the axial part defined as $n_a = 2k = 6$ runs and the coded factors were identified as the coded values of -1.68 and +1.68. The selection of the coded values of the axial part was designed to obtain a rotatable experimental design region which can be achieved by using the value of $\alpha = \pm (2^k)^{1/4} = \pm 1.68$ (Schmidt et al. 1994). By maintaining a rotatable design, the uncertainty of determined response surface symmetry can then be fixed. The remaining runs were set at the center, or $n_c = 6$, with a coded value of 0 as shown in Table 1. The aim of using these center points was to estimate the experimental error and to maintain orthogonality. Furthermore, testing at the center points is more effective for variables that show nonlinear effects on the responses, if any. A minimum number of center points was calculated by the equation proposed by Schmidt et al. (1994), $n_c = [4 * (n_f+1)^{0.5}] - 2k = 6$ runs.

Table 1: The Range of Factors and their Coded Values

Factor	Range	Coded Values				
		–1.68	–1	0	+1	+1.68
A	400 – 500 (kg/m^3)	400	420	450	480	500
B	0.35 – 0.45	0.35	0.37	0.40	0.43	0.45
C	0 – 25%	0	5.1	12.5	19.9	25

The coded values of each factor were calculated based on Equation 1 for five different levels of each variable as described in Table 1. For example, the coded value of water-to-binder ratio of 0.37 can be estimated by using Equation 1 as follows: Coded Factor = (0.37 – 0.4) / (0.5 * 0.06) = –1. The overall range of variables was selected based on reviewing the literature of proportioning SCC containing metakaolin (Vejmelková et al. 2011; Hassan et al. 2012).

[1] Coded Factor = (actual value - central value) / (0.5 * range between maximum and minimum values)

The total number of runs (mixtures) was 20 as described above. By using the previously described levels of each factor for each mixture, the mixture proportions were calculated by applying the absolute volume method. Table 2 outlines the mixture proportions for each run (mixture) in a random order based on the mixing time.

Table 2: Mixture Proportions for the 20 SCC Mixtures

Mixture Number	A: Total Binder (kg/m^3)	B: Water-to-Binder	C: MK Level (%)	Cement (kg/m^3)	MK (kg/m^3)	C. A. (kg/m^3)	F. A. (kg/m^3)	Water (kg/m^3)
1	420	0.37	19.9	336.42	83.58	868.45	964.94	155.4
2	480	0.37	5.1	455.52	24.48	822.98	914.42	177.6
3	450	0.40	12.5	393.75	56.25	828.88	920.98	180.0
4	450	0.40	12.5	393.75	56.25	828.88	920.98	180.0
5	480	0.43	19.9	384.48	95.52	781.10	867.89	206.4
6	450	0.45	12.5	393.75	56.25	801.18	890.19	202.5
7	450	0.35	12.5	393.75	56.25	856.59	951.77	157.5
8	400	0.40	12.5	350.00	50.00	873.63	970.70	160.0
9	420	0.37	5.1	398.58	21.42	874.05	971.17	155.4
10	450	0.40	25.0	337.50	112.5	823.82	915.35	180.0
11	420	0.43	19.9	336.42	83.58	837.41	930.46	180.6
12	450	0.40	12.5	393.75	56.25	828.88	920.98	180.0
13	480	0.43	5.1	455.52	24.48	787.50	875.00	206.4
14	420	0.43	5.1	398.58	21.42	843.02	936.68	180.6
15	450	0.40	12.5	393.75	56.25	828.88	920.98	180.0
16	450	0.40	12.5	393.75	56.25	828.88	920.98	180.0
17	480	0.37	19.9	384.48	95.52	816.57	907.30	177.6
18	500	0.40	12.5	437.50	62.50	784.14	871.27	200.0
19	450	0.40	12.5	393.75	56.25	828.88	920.98	180.0
20	450	0.40	0.0	450.00	0.00	833.95	926.62	180.0

* MK is Metakaolin; C. A. and F. A. are Coarse and Fine Aggregates, respectively

3. Discussion of Test Results

The raw results from each test were subjected to a statistical analysis by means of commercially available program for experimental design. This program performs nonlinear regression analysis for each response (test result) based on the input values (variables). Eventually, the software yields an equation of the response and response surface diagrams can be obtained as well. The developed equations are usually based only on the most significant variables (factors) and their interactions. The equation may be linear or non-linear depending on the behavior of the response throughout the range of variables. Linear equations contain main variables and their interactions, while non-linear formulas include higher order variables (quadratic). The significance of variables and their interactions is determined after completing the analysis of variance (ANOVA). The ANOVA tests the probability values (Probability > F), which indicate that the factor is significant if its value is <0.05. On this basis, the significant variables for each response were selected to form the prediction equations. These equations exhibit some coefficients, which depend on the contribution of each variable. The factor with lower value of Probability > F is preceded by higher coefficients in the respective equation. The equations can be interpreted in forms of coded values or actual values of significant variables. For simplifying the equations, the form of actual values of each variable was applied for models, in this paper.

3.1 Tests on Fresh Properties of SCC

Fresh properties tests were conducted to measure the flowing ability, filling ability, viscosity, passing ability, and segregation of different SCC mixtures. The objective was to study the effect of the total binder, water-to-binder ratio, and percentage of metakaolin on the fresh properties. The results obtained from each test are presented in Table 3, and the derived prediction model for each response is described below in detail:

Table 3: Raw Results of the Fresh Properties for the 20 SCC Mixtures

Mix. No.	HRWRA Dose Litre/m^3	Slump Flow (mm)	T_{500} (Sec)	J-Ring Flow (mm)	T_{500} J-Ring (Sec)	Slump-J-Ring (mm)	V-Funnel (Sec)		L-Box Ratio H2/H1	Air %
							Initial	Final		
1	10.43	629	9.5	604	13.5	25	40	63	0.65	1.7
2	4.00	640	2.5	605	4.5	35	30	48	0.55	1.65
3	4.57	610	3.2	580	5.5	30	24	40	0.67	2.3
4	4.57	650	3.7	621	5.8	29	26	43	0.69	2.1
5	4.86	653	2.0	641	3.0	12	5	6	0.93	3.3
6	3.29	625	2.5	605	3.7	20	4	5	0.77	2.4
7	15.43	673	5.5	636	8.6	37	34	59	0.50	1.45
8	8.14	635	7.2	600	9.3	35	32	55	0.52	1.75
9	8.71	600	8.5	560	11.8	40	36	89	0.45	2
10	7.33	662	4.5	645	5.6	17	30	45	0.78	1.75
11	6.14	650	4.7	634	6.2	16	34	48	0.83	1.4
12	5.29	640	3.5	615	4.4	25	22	35	0.60	1.8
13	2.57	673	1.5	659	2.3	14	3.5	4.5	0.69	1.4
14	3.57	625	3.8	604	6.5	21	8	13	0.68	1.15
15	4.71	640	4.2	610	5.9	30	23	38	0.64	1.7
16	4.57	635	4.0	603	5.3	32	29	46	0.59	1.9
17	9.57	653	6.5	625	8.3	28	24	36	0.80	0.9
18	4.29	625	3.3	605	3.9	20	10	13	0.70	1.9
19	5.29	635	4.5	608	5.8	27	27	45	0.66	2
20	2.33	625	3.0	592	4.0	33	15	34	0.55	2

3.1.1 Flow Ability and Viscosity of SCC

The slump flow test was performed for each SCC mixture after adding a minimum dosage of the HRWRA. The test was repeated by adding additional amounts of HRWRA to reach the diameter of approximately 650 ± 50 mm. The values of the slump flow diameters ranged between 600 - 673 mm, with non-significant differences between the 20 mixtures (see Table 3). It can be also seen in Table 3 that different values of HRWRA demand are warranted depending on the mixture proportions. Thus, the analysis of variance (ANOVA) was performed for the demand of HRWRA and the most significant factors were determined. These factors were B, C, A, B^2, A^2, and AC, respectively (in significance). In addition, a statistical model was developed that relates these factors together in Equation 2 in a logarithmic form, with an R^2 value of (0.95).

[2] $\text{Ln HRWRA Dosage (Litre/m}^3\text{)} = 54.35 - 0.089 * A - 140.898 * B - 0.159 * C + 0.00045 * A * C + 0.000086 * A^2 + 160.291 * B^2$

Although the slump diameter was almost constant for all SCC mixtures, the measured time to reach a diameter of 500 mm (T_{500}) was relatively different. The maximum value of T_{500} was 9.5 seconds, and it was obtained in mixture number 1. This high value of T_{500} reflected the highest viscosity, which was attributed to the low binder content, low water-to-binder ratio, and high replacement of metakaolin. On the other hand, a minimum value of 1.5 seconds occurred in mixture number 13, which demonstrated the minimum viscosity. These results revealed that the increase of the water-to-binder ratio and binder content, and incorporating lower metakaolin replacement, decreased the viscosity of SCC. In addition, the results from the ANOVA for the viscosity (T_{500}) indicated that the most significant factors affecting the mixture viscosity were A, B, and C, respectively. Using these factors, the model for calculating the viscosity was produced as shown in Equation 3 in a logarithmic form, with an R^2 value of (0.85).

[3] $\text{Ln } T_{500} \text{ (Seconds)} = 10.77 - 0.012 * A - 11.14 * B + 0.022 * C$

3.1.2 Passing and Filling Ability of SCC

The passing and filling ability of the SCC mixtures were tested by analysing the results from the J-ring and L-box tests (see Table 3). The results demonstrated that the J-ring diameters were, in general, lower than the diameters of the slump flow. However, the mixture with the highest passing ability had the minimum difference of 12 mm between the two diameters, which was mixture number 5. This result was expected, as the proportions of such mixture exhibited high water-to-binder ratio (0.43), high binder content (480 kg/m^3), and high percentage of metakaolin (19.9%). The maximum difference (40 mm) was associated with mixture number 9, which had low water-to-binder ratio (0.37), low binder content (420 kg/m^3), low replacement of metakaolin (5.1%). For this reason, the prediction model for J-ring diameter was developed by using the difference between slump diameter and J-ring diameter. The factors B, C and A were the most significant factors governing the passing ability of SCC, in terms of difference between the slump and J-ring diameters. The model present in Equation 4 represents the difference between slump and J-ring diameters ($R^2 = 0.8$).

[4] $\text{Slump} - \text{J-Ring Diameter (mm)} = 167.67 - 0.094 * A - 230.51 * B - 0.551 * C$

The same trend was detected when analyzing the results from the L-box test (see Table 3). In this test, the ratio between the heights before and after the obstructing bars was measured (H2/H1). It is clear from Table 3 that the mixture with the minimum difference between J-ring and slump flow (number 5) exhibited the maximum ratio of 0.93 in the L-box test. Similarly, the mixture with the maximum difference between J-ring and slump flow (number 9) had the minimum ratio of 0.45 in the L-box test. The prediction model for the L-box test is described as Equation 5 with the factors B, C, and A significantly affecting the ratio, respectively ($R^2 = 0.86$).

[5] $\text{H2/H1 (L-Box)} = -1.353 + 0.00164 * A + 2.818 * B + 0.0121 * C$

The J-ring test included measuring the time to reach 500 mm diameter through the ring (T_{500} J-ring). This test examines the viscosity and passing ability of SCC by passing the obstructing J-ring bars. The most significant factors governing the value of this test were A, B, and C, respectively. The prediction model obtained from this test is shown in Equation 6, in a logarithmic form ($R^2 = 0.89$). It should be mentioned that all values of J-ring T_{500} were higher than the values of T_{500} without the ring, as expected. This difference was existed because of the obstructing bars of the J-ring which affected the passing ability. Nevertheless, in mixtures with high passing ability (for example, number 13) the difference was not significant (1.5 versus 2.3 seconds). In addition, the maximum value of J-ring T_{500} was 13.5 seconds obtained in mixture number 1 which exhibited the maximum T_{500} (9.5 seconds).

[6] $\text{Ln J-Ring } T_{500} \text{ (Seconds)} = 11.14 - 0.012 * A - 11.023 * B + 0.015 * C$

3.1.3 V-Funnel and Air Content Tests

The V-funnel test was completed over the 20 mixtures primarily to measure the filling ability and viscosity of SCC. The test was performed by filling a V-shaped funnel with fresh concrete, and the amount of time for the concrete to flow out was recorded as Initial V-funnel. The test was repeated by filling the funnel and leaving the concrete to settle for five minutes. After this period, the time required for the concrete to empty out was then measured (final V-funnel) as shown in Table 3. The purpose of repeating the test was to check if the mixture exhibited any segregation. The segregation could have occurred because of settling of the coarse aggregate towards the bottom. It is clear from the values of both initial and final V-funnel times that the final times were higher than initial times, as expected. The difference between the initial and final time ranged between 1 to 53 seconds, present in mixtures number 13 and 9, respectively. After performing ANOVA on the initial V-funnel test, the significant factors were found to be B, A, C, AC, and BC, respectively. For the final V-funnel test, the significant factors were B, A, BC, and C, respectively. Equations 7 and 8 show the prediction models for the initial and final V-funnel times ($R^2 = 0.94$; $R^2 = 0.92$, respectively).

[7] $\text{Initial V-Funnel (Seconds)} = 220.78 + 0.016 * A - 528.66 * B + 2.61 * C - 0.0195 * A * C + 16.69 * B * C$

[8] $\text{Final V-Funnel (Seconds)} = 707.58 - 0.47 * A - 1154.67 * B - 16.67 * C + 42.09 * B * C$

The air content test was implemented for the twenty mixtures and the results yielded a range 0.9 to 3.3%, as shown in Table 3. It should be noted that no air entrainment agent was added in the mixtures and the measured air content represented the trapped air. The model to evaluate the air content of SCC mixtures can be seen in Equation 9 ($R^2 = 0.7$). This model showed that the most significant governing factors were AB, BC, B, A, and C, respectively.

[9] $\text{Air Content (\%)} = 90.85 - 0.184 * A - 226.24 * B - 0.717 * C + 0.47 * A * B + 1.81 * B * C$

3.2 Tests on Mechanical and Durability Properties of SCC

After the curing period of 28 days, SCC cylinders were tested to evaluate the compressive strength and the chloride permeability of each mixture. The chloride permeability was measured by means of the rapid chloride penetration test (RCPT), following the ASTM C1202. The results obtained from the two tests are introduced in Figures 1 and 2, both for air and water curing.

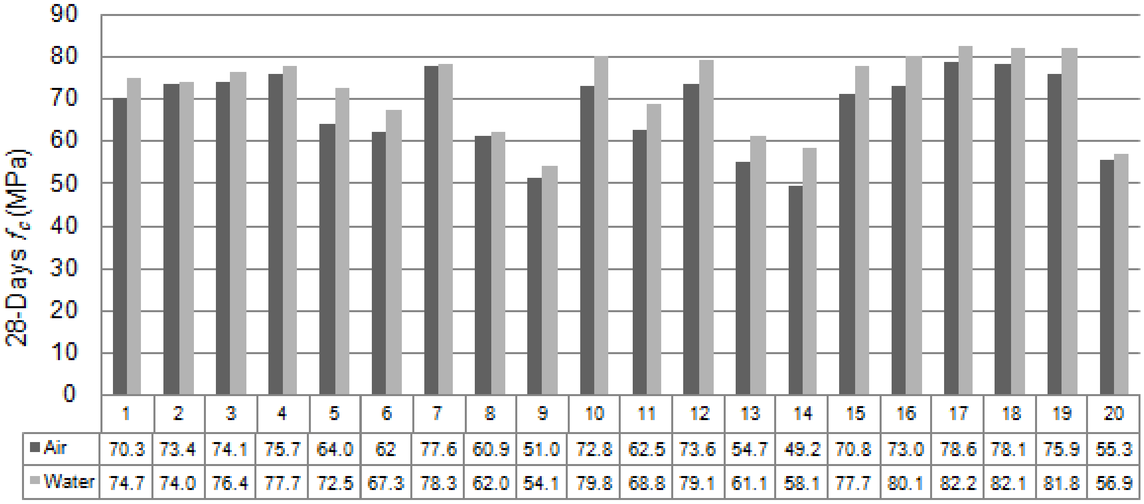
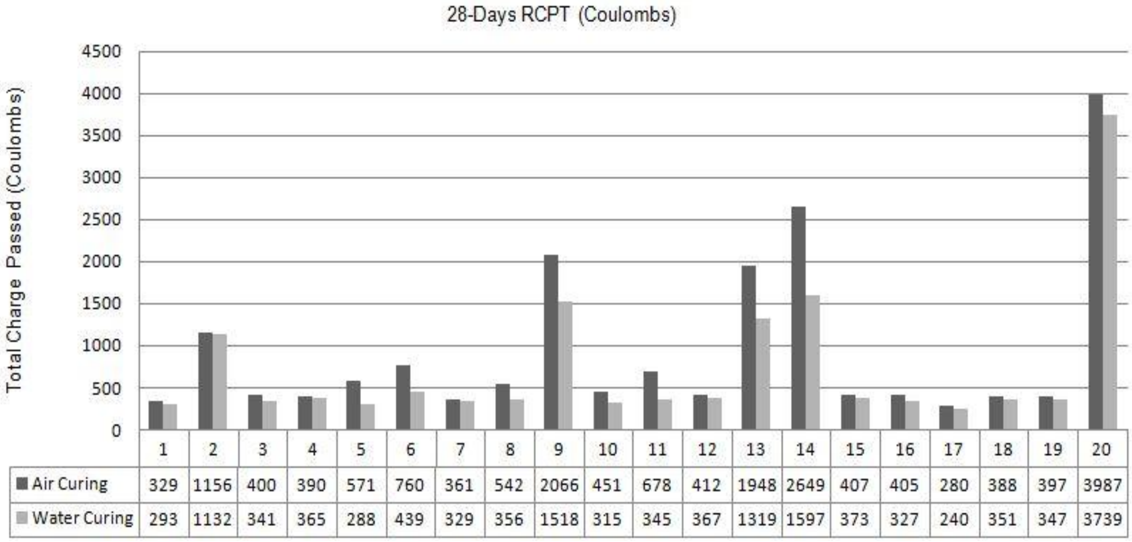


Figure 1: 28-Days Compressive Strength of the 20 SCC Mixtures (MPa)



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
■ Air Curing	329	1156	400	390	571	760	361	542	2066	451	678	412	1948	2649	407	405	280	388	397	3987
■ Water Curing	293	1132	341	365	288	439	329	356	1518	315	345	367	1319	1597	373	327	240	351	347	3739

Figure 2: 28-Days RCPT of the 20 SCC Mixtures (Coulombs)

3.2.1 Models for Compressive Strength of SCC

An ANOVA analysis was completed similarly for both results from air and water curing to select the most significant affecting factors. The significant factors were C, B, A, C^2, A^2, B^2, and AB, respectively and the associated models were developed, in Equations 10 and 11 ($R^2 = 0.92$; $R^2 = 0.94$, respectively). It is clear from the equations that both models are based on the same variables representing the same trend. However, as seen in Figure 1, the results of water curing samples exhibited higher values than air curing counterparts, as expected. The maximum strength was obtained from mixture number 17; while the minimum was associated with number 9 (see Figure 1). This result was attributed to the high binder content and replacement of metakaolin, and the low water-to-binder ratio included in the mixture (number 17).

[10] 28-Days Compressive Strength (Air Curing) $= -1556.48 + 4.03 * A + 3493.7 * B + 2.75 * C - 3.36 * A * B - 0.003 * A^2 - 2687.76 * B^2 - 0.08 * C^2$ (MPa)

[11] 28-Days Compressive Strength (Water Curing) $= -1648.77 + 4.29 * A + 3610.22 * B + 2.78 * C - 2.94 * A * B - 0.003 * A^2 - 2994.08 * B^2 - 0.08 * C^2$ (MPa)

3.2.2 Models for Chloride Permeability of SCC

Following the same analysis procedure, the prediction models for chloride permeability were obtained in the logarithmic form of the total charge passed in the RCPT. The model in Equation 12 predicts the chloride permeability of air curing samples. In this model, the most important variables were C, C^2, B, B^2, A, and A^2, respectively, with ($R^2 = 0.97$). Alternatively, the model for water curing model included only C, C^2, B, A as the most significant factors, respectively, with ($R^2 = 0.98$), as seen in Equation 13. It is obvious from Figure 2 that minimum chloride permeability was obtained from the mixture number 17, which had the maximum compressive strength. On the contrary, the maximum permeability was related to mixture number 20, which had no metakaolin (0%). This result manifests the effect of metakaolin in reducing the chloride permeability of SCC.

[12] Ln 28-Days RCPT (Air Curing) $= 55.75 - 0.104 * A - 122.66 * B - 0.31 * C + 0.000111 * A^2 + 163.98 * B^2 + 0.\ 0086 * C^2$ (Coulombs)

[13] Ln 28-Days RCPT (Water Curing) $= 8.37 - 0.0022 * A + 2.55 * B - 0.294 * C + 0.\ 0076 * C^2$ (Coulombs)

3.2.3 Effect of Curing on the Compressive Strength and Chloride Permeability of SCC

The results of the compressive strength and chloride permeability tests for both air- and water-cured samples are plotted, for each SCC mixtures, in Figures 1 and 2. The compressive strength of water-cured samples was slightly higher than their air-cured counterparts. Although the difference was non-significant in almost all mixtures, it was higher in mixtures number 5, 6, 11, 13 and 14. This difference was attributed to the high water-to-binder ratio (greater than 0.4) present in these mixtures.

The results of the RCPT test indicate that the chloride permeability is low when the total passed charge in coulombs is low. It can be seen from Figure 2 that an identical trend was obtained from the chloride permeability of both air- and water-cured samples. In the chart, the water-cured samples show lower permeability than air-cured ones throughout the 20 mixtures. In addition, the significant difference between air- and water-cured results was also obvious within the same mixtures (5, 6, 11, 13 and 14). This difference indicated that water curing is a significant factor affecting the strength and permeability of SCC, especially when higher water-to-binder ratios are used (>0.4).

3.3 Optimization of SCC Mixture and Models Validation

By reviewing the results from both the fresh and hardened properties of the 20 mixtures, the optimum mixtures were number 5 and 17, respectively. These two mixtures both had a binder content of 480 kg/m^3 and a metakaolin percent of 19.9%. It is clear that the mixture with high water-to-binder ratio (0.43) had the optimum fresh properties (mixture number 5), as expected. Moreover, the mixture with low water-to-binder ratio (0.37) had the maximum strength and the minimum chloride permeability (mixture number 17). In order to determine one mixture achieving the balance between fresh properties, strength, and durability, the numerical optimization tool was utilized. This tool is available with the method of central composite design (CCD) in the commercially used software. The target in this technique was established to maximize the flow ability, passing ability, and compressive strength; and minimize the chloride permeability of the SCC mixture. In this optimization, the developed prediction models were used along with the pre-defined targets, in a number of trials which maintain the desired criteria.

The results yielded an optimum SCC mixture having the following ingredients: A (Total Binder = 490 kg/m^3), B (W/B = 0.39), and C (Metakaolin Ratio = 19.9%). This optimum mixture was tested under the same procedure to validate the prediction models and the results are compared in Table 4. It can be seen that the results obtained from the prediction models are relatively close to the actual test results. However, the differences can be attributed to the higher dosage of the HRWRA added in the actual test than the required amount predicted in the model. It should be mentioned that the differences are lower in the results of compressive strength and chloride permeability than that in the fresh properties.

Table 4: Comparison and Validating Prediction Models

Mixture Number	HRWRA Dose Litre/m^3	T_{500} (Sec)	T_{500} J-Ring (Sec)	Slump – J-Ring (mm)	V-Funnel (Sec)		L-Box Ratio H2/H1	Air %
					Initial	Final		
Predicted	7.71	3.25	4.29	21	13	24	0.79	2.1
Tested	10.77	3.5	4	18	8	11	0.80	1.0

Mixture Number	28-Days Compressive Strength (MPa)		28-Days RCPT (Coulombs)	
	Air Curing	Water Curing	Air Curing	Water Curing
Predicted	80.11	84.67	299	239
Tested	74.65	82.1	268	217

4. Conclusions

In this paper, the CCD statistical analysis method was applied to 20 SCC mixtures containing metakaolin with varying mixture proportions. Tests on the fresh properties, compressive strength, and chloride permeability were performed on the 20 mixtures, and prediction models were developed for each test. The models were validated by testing an additional SCC mixture and comparing experimental results with the predicted values. Finally, a numerical optimization was completed to optimize the mixture proportions, and the following conclusions are drawn:

- An optimum SCC mixture that can maintain the required balance between fresh properties, strength, and chloride permeability, showed to contain a total binder of 490 kg/m^3, water-to-binder ratio of 0.39, and a replacement of metakaolin by 19.9%.

- Incorporating metakaolin in the SCC mixture resulted in an increase in the passing ability, viscosity, compressive strength, and a decrease in chloride permeability of SCC.

- The prediction models can be used as a useful tool to evaluate different SCC mixtures containing metakaolin.

- The effects of the three variables were almost linear for the fresh properties tests; however, for compressive strength and chloride permeability test these effects were completely non-linear.

- Different curing techniques had a significant effect on both compressive strength and permeability of SCC. In addition, water-cured samples had higher strength and lower permeability than their air-cured counterparts.

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