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OPTIMIZATION OF SELF-COMPACTING CONCRETE USING RESPONSE SURFACE METHODOLOGY

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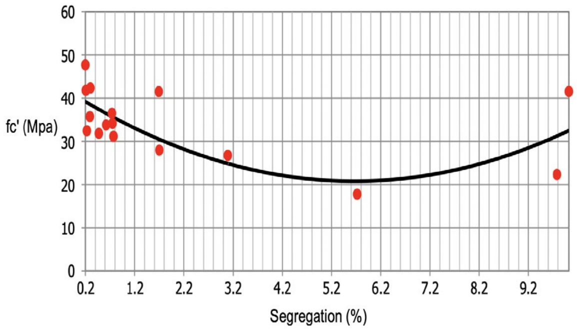
Graphical abstract



Abstract

The development of predicting models is necessary for an easier and more accurate design mix of self-compacting concrete. Due to the difficulty of test requirements for this type of concrete, a predicting model is useful and can be used to derive the optimum design mix. Different mixtures with varying cement, water, and superplasticizer content were created using a central composite design. A full quadratic model was chosen for all dependent variables considered such as flowability, passing ability, resistance to segregation, 28th-day compressive strength, and flexural strength. Water is the only significant factor that affects all of the rheological properties and compressive strength. Mixtures with high superplasticizer and water content show high segregation and bleeding but yield high compressive strength. Surface response and interaction profiles are developed to help the user of the models in modifying their design mix. Response surface methodology (RSM) was used to derive the optimum. The derived optimum design mix is as follows, cement is 483.72kg, 250kg for the water, and 1% for the superplasticizer The optimum design mix of SCC has a desirability of 0.812. The optimum design yield passing slump flow of 609.22mm (>550mm passing), passing l-box of 0.915 (>0.80 passing), -0.962% which can be assumed as equal to zero (<15% passing), 41.79Mpa for compressive strength and 10.33Mpa for flexural strength. The optimum design passes all rheological requirements and has acceptable compressive and flexural strengths. Although the mixture has high water content, this is due to the requirement of rheology. Low superplasticizer content is ideal for limiting segregation and bleeding.

Keywords: Bleeding, Optimization, Response Surface Methodology, Rheology, Self-Compacting Concrete,

1.0 INTRODUCTION

Self-compacting concrete (SCC) is one of the improved types of concrete that has a significant advantage over conventional concrete. Comparing it to conventional concrete, it has better workability and better mechanical properties. Numerous research papers also suggest that SCC has better corrosion resistance than other types of concrete [1,2,3]. SCC is usually used for rebar-congested structures but can be applied to all types of cast-in-place construction. This project is exploring the possibility of using SCC as a better concrete for a chloride-rich environment. The project's initial step is to develop design mixes and the optimum design of SCC.

Constituents of SCC are common to normal concrete except for the addition of admixtures such as superplasticizers and viscosity agents and mineral admixtures. In, the Philippines, SCC is seldom used because of the lack of understanding of this new type of concrete. SCC is still not included in the standard type of concrete for government projects in the Philippines. Also, it is still not considered a common type of concrete used in construction even after more than 30 years of existence.

Designing self-compacting concrete is a difficult undertaking because of the numerous requirements in the rheological properties and compressive strength [4]. Commonly, users of this type of concrete use a trial-and-error method for designing it. There are several guidelines for designing SCC but still, the difficulty exists because of the interaction of its components [5]. Water and superplasticizer are the two most common factors that affect the rheology and strength of the concrete [4]. A correct combination of the two ingredients together with the variation in the cement and aggregate content is necessary to achieve the desired rheology of concrete. Incorrect combinations of the variables will lead to segregation, bleeding, and possibly, insufficient workability [6].

This paper develops models that predict all rheological properties of SCC such as flowability, passing ability, and segregation resistance which is based on the results of different tests in accordance with EFNARC [7]. Compressive and flexural strength are also considered in the modeling. Charts were developed to assist the end users of the models. The optimum design mix was determined to give an idea of the best combination of the three variables considered. Regression analysis was used to determine the accuracy of the derived models.

2.0 METHODOLOGY

2.1 Design Mix of SCC

This research derived different models that can predict the rheological properties, compressive strength, and flexural strength of SCC. The accuracy of the models was also tested together with the parametric study. The optimum design mix was calculated using the derived models. Sixteen different mixtures were designed using Central Composite Design (CCD) as shown in Table 1. CCD was chosen due to the limitations of conducting a full factorial analysis and its ability for a second-order quadratic model. Different amounts of cement (430, 465, and 500 kg/m^3), water (210, 230, and 250 kg/ m3), and superplasticizer (1%, 1.4%, and 1.8%) were mixed with a fixed amount of fine (910kg/ m3) and coarse aggregates (700kg/m^3). The range for the superplasticizer was based on the manufacturers' recommendation of 0.8% to 2.0% of cementitious materials. The researchers opted to adjust from 1.0% to 1.8% based on the initial testing conducted.

The dry components (cement, sand, and coarse aggregates) were mixed in a half-bagger mixer for 3 minutes, then two-thirds of the mixing water together with the superplasticizer was added and mixed until a balling effect was achieved (approximately 5-10 minutes). Lastly, the remaining mixing water was added and mixed for another 3-5 minutes.

Table 1 Design Mix of SCC

No.	Design	Cement	Water	SP %	Gravel kg	Sand kg
1	++-	500	250	1	700	910
2	+−+	500	210	1.8	700	910
3	−−−	430	210	1	700	910
4	−−+	430	210	1.8	700	910
5	A00	500	230	1.4	700	910
6	a00	430	230	1.4	700	910
7	+−−	500	210	1	700	910
8	0A0	465	250	1.4	700	910
9	000	465	230	1.4	700	910
10	−+−	430	250	1	700	910
11	00A	465	230	1.8	700	910
12	000	465	230	1.4	700	910
13	00a	465	230	1	700	910
14	+++	500	250	1.8	700	910
15	−++	430	250	1.8	700	910
16	0a0	465	210	1.4	700	910

2.2 Rheological Test

All mixtures were tested on the different rheological properties of SCC such as flow ability (Slump Flow), passing ability (L-Box), viscosity (T50), and resistance to segregation (GTM Screen Stability Test) based on the standard of EFNARC (Figure 1). The passing value for each test is listed in the last row of Table 2.

Flow Ability **Passing Ability** **Segregation Resistance**

Slump Flow Using Abrams Cone ≥550mm

L-Box with 2 Bars ≥0.8

GTM Screen Stability Test <20%

Figure 1. Rheological Tests [7]

2.3 Strength Test

Twenty-eighth-day compressive strength was also determined using 3 samples of 100mm diameter by 200mm height cylinder (Figure 2). Flexural strength was also tested using a 100mm by 100mm by 350mm length beam tested using center-point loading as shown in Table 3.

Compressive Strength **Flexural Strength**

DATE MIXED: DAY 9 10-25
MIX TYPE: 2
SPECIMEN No: B
DIAMETER: ⓐ 101
mm ⓑ 101.1
LENGTH: ⓐ 200.9
mm ⓑ 200.6
ⓒ 201.2
WEIGHT: 3.760 kg
DATE TODAY: 11.22.2021

100mm(diameter) x 200mm(height) cylinder cured for 28 days

100mm(height) x 100mm(width) x 350mm(length) beam cured for 28 days Tested using UTM, center point loading

Figure 2. Strength Tests [7]

2.4 Modeling and Optimization

Response surface methodology was used to derive the models to forecast the relationship between the dependent and independent variables. There were 5 models derived which are flow ability, passing ability, segregation resistance, compressive strength, and flexural strength which are all based on three parameters such as cement content, water content, and superplasticizer dosage.

The best model for each property was chosen between the first-order model (Eq. 1) and the second-order model (Eq. 2) based on the value of the R-squared. A response surface plot (Eq. 3) was also developed to visualize the response of each variable to the output [8]. The variable y is the dependent variable, x is the independent variable(s), β is the population slope(s) and ε is the random error.

$$y_i = \beta_0 + \beta_1 x_{i1} + \beta_2 \beta_{i2} + \cdots \beta_q \beta_{iq} + \varepsilon_i \qquad (1)$$

$$y = \beta_0 + \sum_{i=1}^{q} \beta_i x_i + \sum_{i=1}^{q} \beta_{ii} {x_i}^2 + \sum \sum_{i<j} \beta_{ij} x_i x_j + \varepsilon \qquad (2)$$

$$y = f(x_1, x_2) + \varepsilon \qquad (3)$$

3.0 RESULTS AND DISCUSSION

3.1 Rheological, Compressive, and Flexural Strength Tests Results

Tables 2 and 3 below show the result of rheological and mechanical tests performed for all 16 different mixtures. Some mixtures did not pass for slump flow, T50, and L-box. The reason for this is the too much viscosity of the mixture because of the high amount of fine materials (cement and sand) [9]. All mixtures with low water content regardless of the dosage of superplasticizer failed to the requirement of flowability (SF) and passing ability (L-box).

Table 2. Slump Flow, T50, and L-Box Results

No.	Design	SF (mm)	Remarks	T50 (sec)	L-Box	Remarks
1	++--	610	Passed	1	0.95	passed
2	+−+	470	failed	ND	0.12	failed
3	−−−	460	failed	ND	0.33	failed
4	−−+	540	failed	8	0.29	failed
5	A00	650	Passed	2	0.85	passed
6	a00	540	failed	2	0.63	failed
7	+−−	300	failed	ND	0	failed
8	0A0	630	Passed	2	0.8	passed
9	000	560	Passed	3	0.75	failed
10	−+−	630	Passed	2	0.8	passed
11	00A	575	Passed	2	0.57	failed
12	000	565	Passed	3	0.84	passed
13	00a	540	failed	2.5	0.72	failed
14	+++	720	Passed	1	1	passed
15	−++	665	Passed	1	0.67	failed
16	0a0	470	failed	ND	0.41	failed

*ND- no data

Mixture +++ with high cement, water, and SP content yields the highest segregation which reduces the flowability significantly [4][7][10]. Bleeding was also observed in this mixture. Superplasticizers are surfactants that make the cement negatively charge which resulted in a more dispersed state [11,12] In this way, the excess water will be repelled and because it is the lightest material in concrete, the tendency is to go upward at the surface. Mixtures with the highest amount of water (250kg) combined with the highest amount of superplasticizer (1.8%) show slight bleeding which resulted in the highest segregation of (10.02%) among all mixtures. Although all mixtures passed the requirement for segregation due to the high amount of fine aggregates (910kg/m^3) that control the viscosity of the concrete.

Mixtures with the lowest amount of water did not pass the requirement for slump flow by the standard of EFNARC 2005 as well as for L-box, these mixtures were dry and did not show workability. Most of the concrete mixtures failed in the passing ability and slump flow either has low water, low SP, or both.

Table 3. GTM, Compressive Strength, and Flexural Strength

Design	GTM (%)	Remarks	fc' (Mpa)	Fb (Mpa)
++-	0.3	passed	42.35	8.99
+−+	0.21	passed	41.83	6.10
−−−	0.29	passed	35.75	8.95
−−+	0.75	passed	34.17	9.10
A00	1.7	passed	27.98	8.34
a00	5.72	passed	17.77	8.64
+−−	0.2	passed	47.71	10.23
0A0	3.09	passed	26.76	10.02
000	0.62	passed	33.81	10.39
−+−	0.77	passed	31.18	9.56
00A	1.69	passed	41.54	10.88
000	0.74	passed	36.50	9.28
00a	0.47	passed	31.84	10.13
+++	10.02	passed	41.57	9.77
−++	9.78	passed	22.33	9.71
0a0	0.23	passed	32.45	10.76

3.2 Derived Models

The models were derived using the JMP software. The models were all full quadratic. Second-order polynomials were included in the derived models. Tables 4 and 5 show the coefficients and p-values of each factor for each derived model. The influences of each factor can be measured from its coefficient derived using the least square method.

Water has the highest influence on the flow ability and passing ability of the SCC. On the other hand, the interaction between water and superplasticizer influenced most of the segregation resistance of the concrete. Water has a negative impact (-2.772) on the compressive strength which is an established fact, but combining water with a superplasticizer can yield erratic behavior of the rheological and compressive strength of the concrete [4].

Bleeding can influence the results of the rheological properties and strength of the concrete. It is necessary to control the amount of water and superplasticizer to prevent bleeding. Most manufacturers of superplasticizers have their own recommendations for their dosage. In SCC, bleeding is usually a function of water (p-value <0.005), but the amount of SP (p-value 0.0057) and the interaction between the two variables (p-value 0.0057) were also notable contributors in the result as seen on the GTM test [13].

Table 4. Coefficients, T-Ratios and P-Values of Rheological Models

Variables	Slump Flow		L-Box		GTM	
	Coef.	P-Value	Coef.	P-Value	Coef.	P-Value
Intercept	570.26	<.0001	0.7619	<.0001	1.3145	0.1206
Cement	-8.50	0.5863	0.02	0.576	-0.488	0.3537
Water	101.50	0.0005	0.307	0.0001	2.228	0.0037
SP	43.00	0.0271	-0.015	0.6731	2.042	0.0057
Cement*Water	33.13	0.0920	0.1225	0.0177	0.05	0.9296
Cement*SP	20.63	0.2587	0.0425	0.3041	0.0325	0.9542
Water*SP	-13.13	0.4575	-0.02	0.616	2.2825	0.0057
Cement*Cement	20.86	0.4961	-0.0053	0.938	2.0783	0.0703
Water*Water	-24.14	0.4341	-0.1403	0.0772	0.0283	0.9771
SP*SP	-16.64	0.5845	-0.1003	0.1786	0.5517	0.5808

Table 5. Coefficients, T-Ratios, and P-Values of Strength Test Models

Variables	Compressive Strength		Flexural Strength	
	Coef.	P-Value	Coef.	P-Value
Intercept	30.12017	<.0001	10.0181	<.0001
Cement	6.024	0.5863	-0.253	0.4463
Water	-2.772	0.0005	0.291	0.3848
SP	-0.739	0.0271	-0.23	0.4868
Cement*Water	1.34875	0.092	0.15125	0.6783
Cement*SP	0.47125	0.2587	-0.45625	0.2368
Water*SP	-0.27125	0.4575	0.61375	0.1275
Cement*Cement	-4.72776	0.4961	-1.61966	0.0366
Water*Water	2.002241	0.4341	0.280345	0.6593
SP*SP	9.087241	0.5845	0.395345	0.5375

3.3 Regression Analysis

The accuracy of the derived models is tested by solving the R-squared of the plotted actual test results versus the predicted results. All values are normalized between 0 (lowest) and 1 (highest) (See Figure 3). The result shows that the L-box model has the best accuracy with an R-squared of 0.948, followed by Slump (0.9138) and GTM (0.9133). The two strength models have R^2 values of 0.7939 (fc’) and 0.7099 (flexural strength). This means that the derived models can be used to accurately design the mixture of self-compacting concrete considering all rheological properties, and compressive and flexural strength.

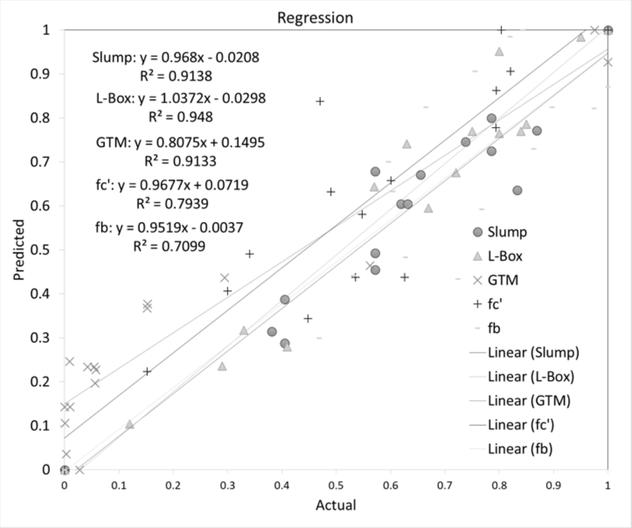


Figure 3. Regression Analysis

3.4 Surface Response

Figure 4 shows that the slump flow of SCC was greatly affected by the two factors such as water and superplasticizer. High values of cement, water, and superplasticizer yield the highest flow according to Figure 4. A high amount of cement in the mixture with high water and dosage of SP is beneficial in controlling segregation (See Figure 6) [14]. Segregation and bleeding in concrete will result in a decrease in workability because of the separation of the water in the mixture. It is advisable to design an SCC with moderate water content combined with low SP content and this will yield passing flowability to decrease the risk of segregation [15]. Moderate to high SP with low water content will also generate good flowability but is more viscous than the previously cited mixture.

Moderate to high water content (230L-250L) and cement (465kg-500kg) combined with a low to moderate dosage of superplasticizer (1.0%-1.4%) is the ideal range for mixtures of SCC that passed the requirements of EFNARC. Unlike flowability, passing ability requires the concrete to have the right level of viscosity since the separation of coarse aggregates from the mixture will result in the blockage of the opening of the L-box apparatus (see Figure 5).

Mixtures with a high dosage of superplasticizer and a high amount of water regardless of the amount of cement yield high segregation (but considered passing; <15%). Based on observation during the test, bleeding is the main reason for the high result in the GTM test. The excess water that leaked out of the mixture due to the bleeding passed through the sieve in the GTM test which resulted in high bleeding.

Mixtures with low water and superplasticizer combined with a high amount of cement yield the highest compressive strength but lack workability. As shown in Figure 7, ideally, mixtures with low water content will yield higher compressive strength than mixtures with a high amount of water. But in the case of a mixture containing a high amount of SP and water, the compressive strength increases. The possible explanation for the increase in the compressive strength of the samples that show bleeding is the reduction of water content which resulted in fewer voids when it hardens [16]. The slight bleeding may be considered helpful in the compaction of the mixture. Only the outermost top part of the samples shows slight powdery particles but may not affect the resulting compressive strength of the cylindrical samples. Figure 8 shows the behavior of the model for the flexural strength of SCC. It shows similar behavior to compressive strength test results.

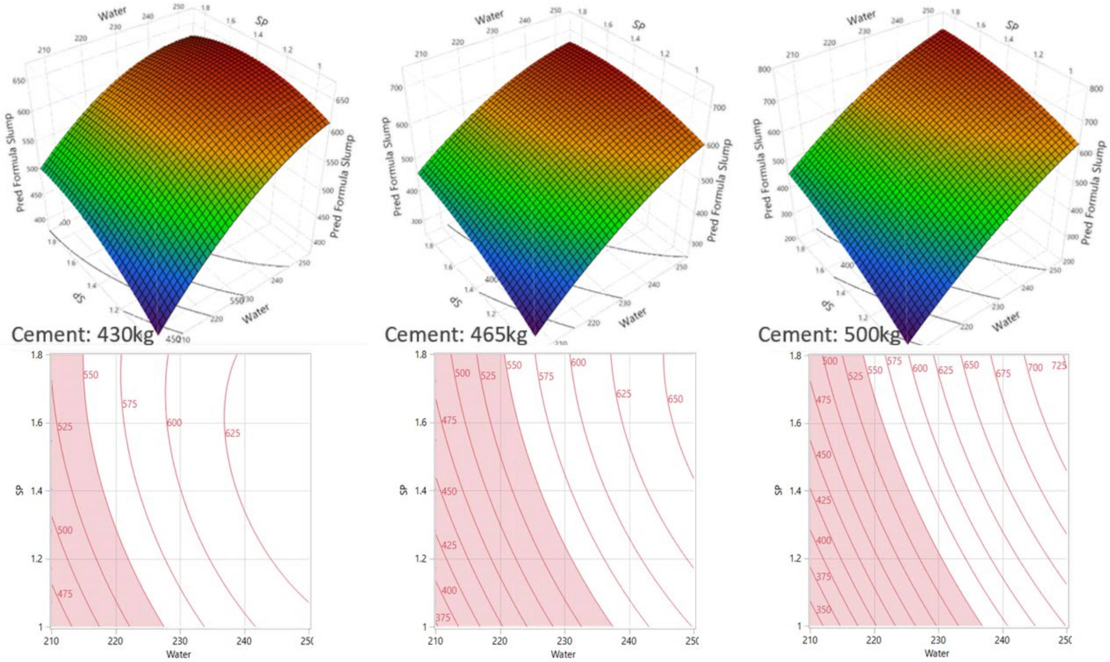


Figure 4. Response Surface of Slump Flow

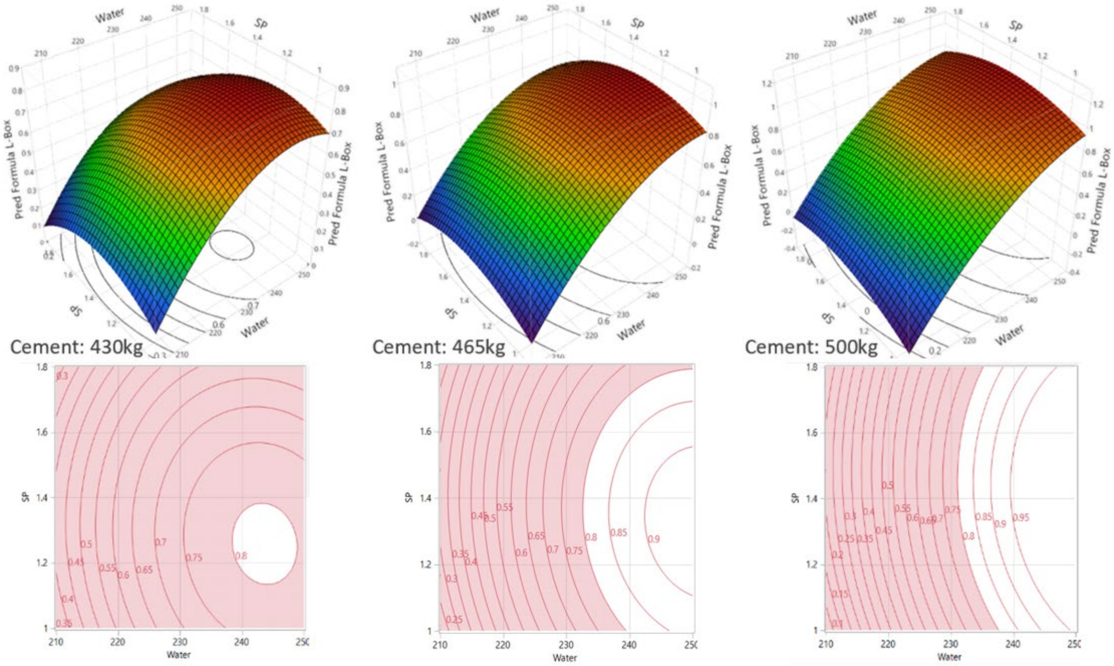


Figure 5. Response Surface of L-Box

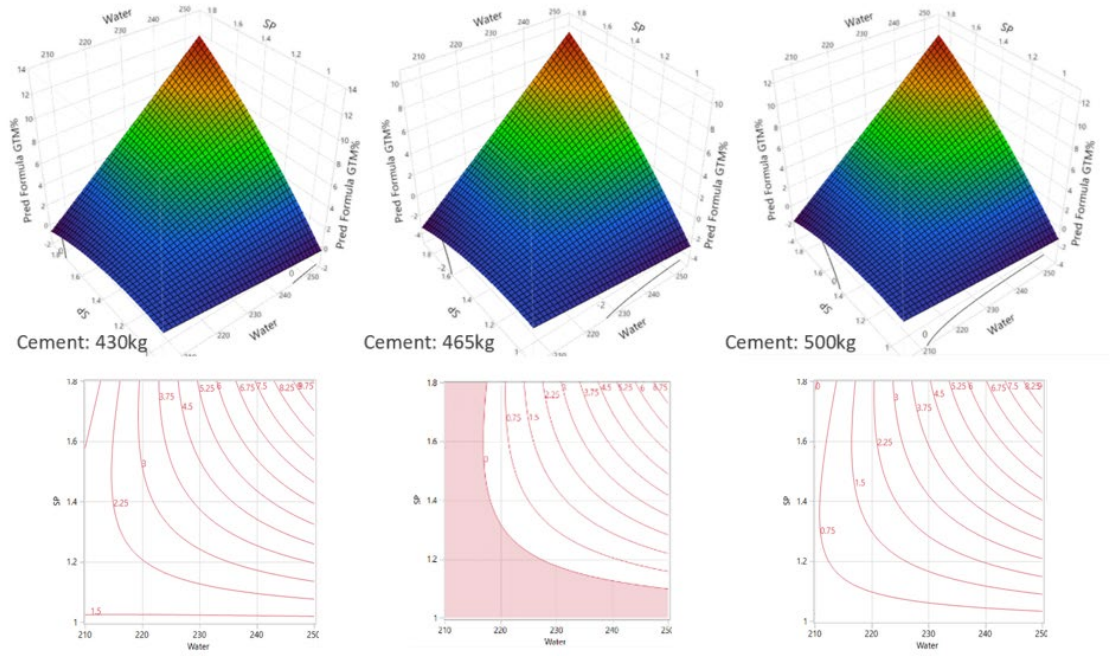


Figure 6. Response Surface of GTM

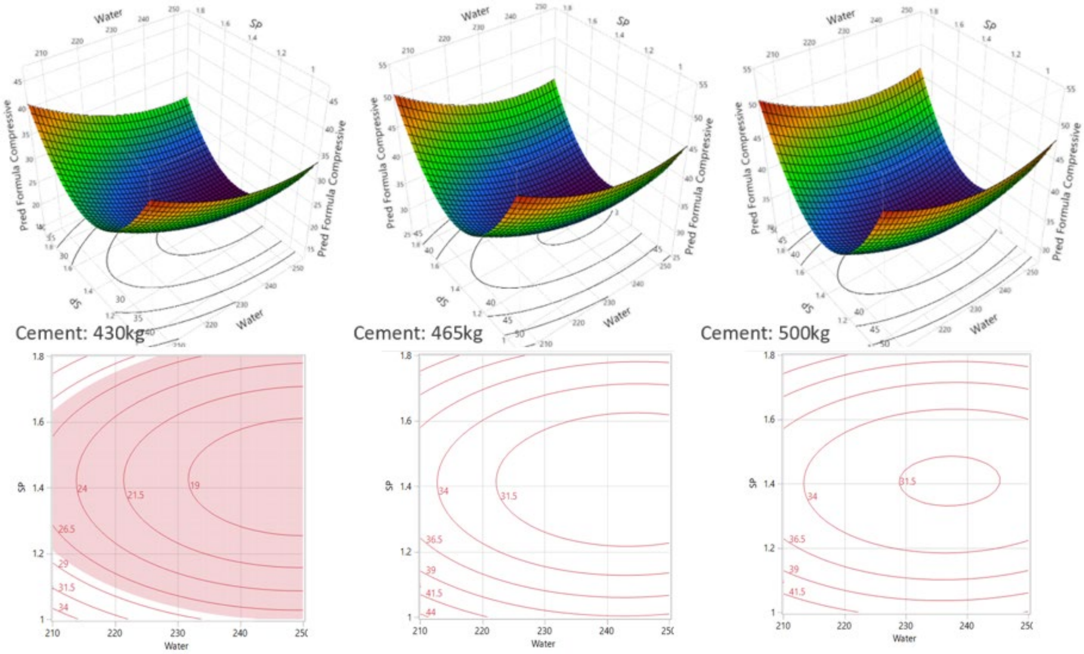


Figure 7. Response Surface of Compressive Strength

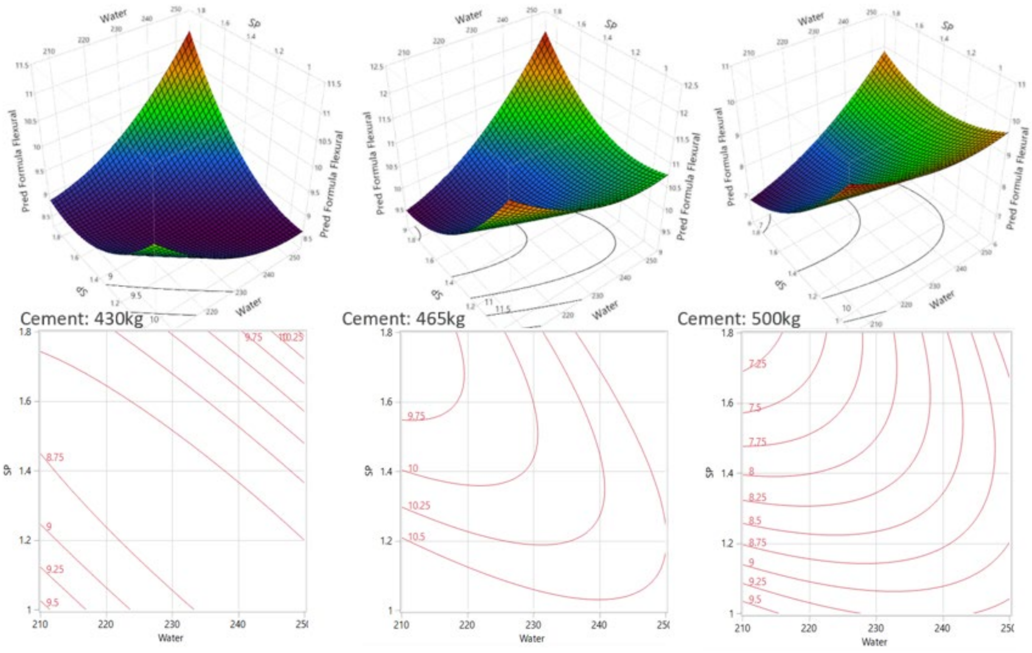
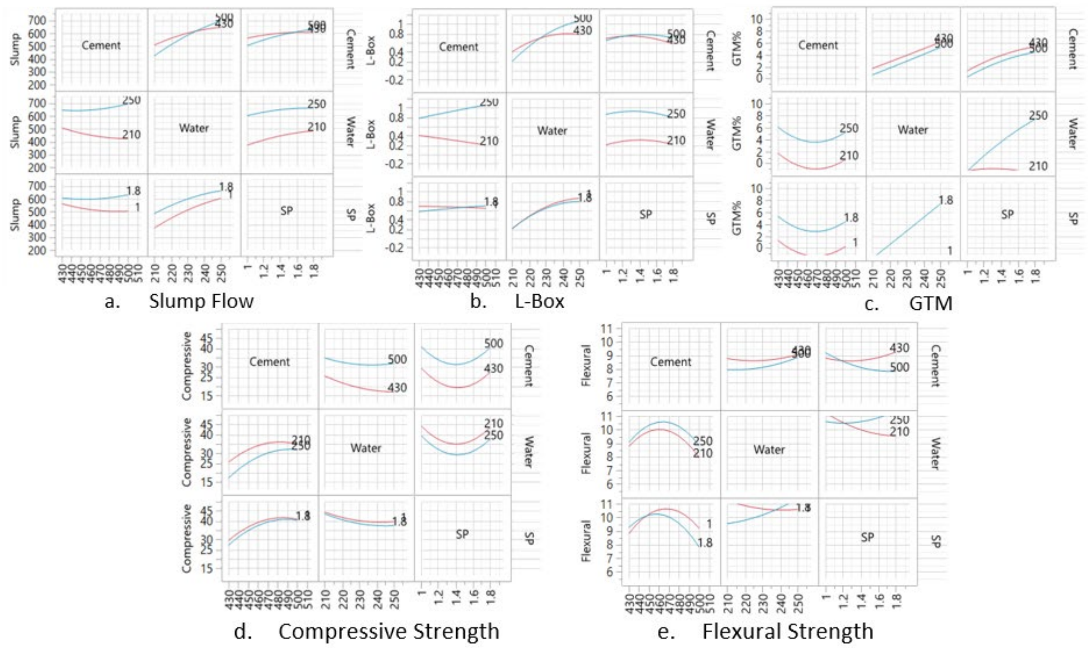


Figure 8. Response Surface of Flexural Strength



a. Slump Flow
b. L-Box
c. GTM
d. Compressive Strength
e. Flexural Strength

Figure 9. Interaction Profiles

According to [16][17], low bleeding of 0.3% can increase the compressive strength of the concrete. This is due to the increase in the density and compaction of the concrete because of a decrease in the excess water. According to the study of [18], bleeding may lower the strength of concrete by about 30% in the full-scale specimen but may not affect or have a negative effect on small cylindrical specimens. This phenomenon should be investigated further considering different factors such as the amount of cement, water, superplasticizer, amount and size distribution of fine and coarse aggregates, and the rate of bleeding.

To validate the result of the compressive strength and to verify the explanation behind the effect of bleeding, the result of the segregation test was plotted against the compressive strength. A quadratic trend was observed in the relationship between the two variables with an R-squared of 0.463. A downward trend in the compressive strength is observed when the segregation of concrete is between 0% to 6% but suddenly increased beyond the 6% segregation level See Figure 10. The reason for this behavior is because of the loss of excess water in the mixtures. Since the samples are contained in a cylinder, due to bleeding, the water (which has the lowest density among SCC constituents) travels upward to the top of the specimen. This is the reason for a more compact specimen which resulted in higher compressive strength.

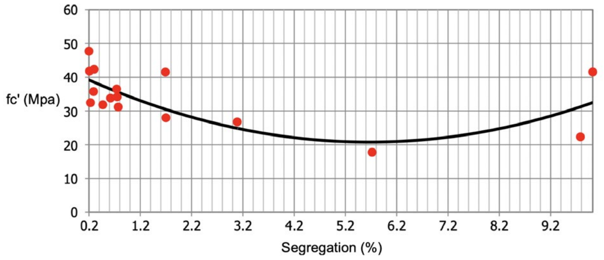


Figure 10. Response Surface of Compressive Strength

Similar results were observed in the flexural strength test. Mixtures with low water content resulted in high flexural strength. Mixtures that show slight bleeding (with a high amount of SP) [19] show high flexural strength similar to low water content mixtures. One factor that may affect why the bleeding does not significantly affect the strength of self-compacting concrete is the presence of a superplasticizer. The cement particles were coated by this admixture, which repels the excess water. In our observation, most of the water that bleeds in the concrete is almost clean and free from cement particles.

3.5 Interaction Profiles

Figure 9 shows the interaction between parameters. For the rheological properties of SCC, all parameters such as water, cement, and SP agree with the established trend in the literature. Water is the only significant factor affecting SCC's rheology and compressive strength. Different dosages of superplasticizers show erratic behavior for the passing ability and compressive strength. An increase in the SP dosage significantly impacts the result of the GTM test. Interaction profiles shown in Figure 8 can be used as a guide for designing self-compacting concrete.

3.6 Optimum Design Mix

All five dependent variables are considered in the optimum design mix of the concrete (see Figure 11). The highest setting was set for slump flow, l-box, compressive strength, and flexural strength meanwhile, the segregation is set to zero. According to the result of optimization, the required cement content is 483.72kg, 250kg for the water, and 1% for the superplasticizer. The optimum design yield passing slump flow of 609.22mm (>550mm passing), passing l-box of 0.915 (>0.80 passing), -0.962% which can be assumed as equal to zero (<15% passing), 41.79Mpa for compressive strength and 10.33Mpa for flexural strength.

The derived optimum design mix has a desirability of 0.812. The reason for having a mixture with high water content is the requirement of workability specifically, due to the requirement of slump flow and l-box. Based on the experience of the researchers, increasing the amount of water is more beneficial to the concrete in terms of enhancing its workability rather than increasing the amount of SP which will result in excessive bleeding. Since the mixtures used in the experiment have a significant amount of fine (cement and fine aggregates), it requires high water demand to have good rheological properties. Decreasing powder content is an option to decrease the viscosity which will decrease the water demand of the SCC mixture [7],[20].

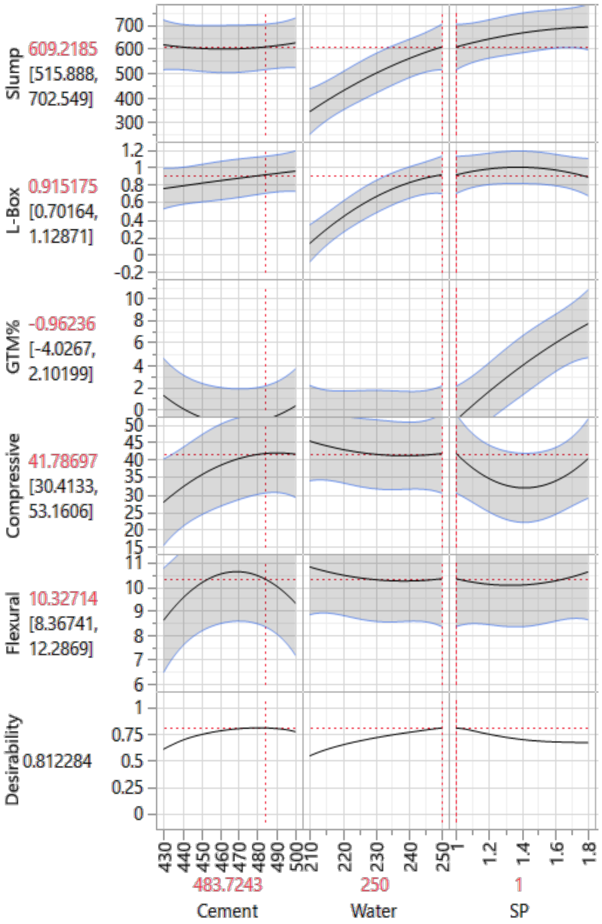


Figure 11. Optimum Design Mix

4.0 CONCLUSION

Self-compacting concrete is one of the most challenging types of concrete because of its erratic behavior. Different combinations of factors (cement, water, and SP) will yield different results and the repeatability of every test for rheological properties was hard to achieve.

Based on the derived models, water is the most influential factor among all dependent variables considered in this research. SP on the other hand has erratic behavior because of the effect of bleeding and segregation. Mixtures with a high SP dosage (1.8%) yield slight bleeding and segregation. This affected the rheological properties of the concrete as well as the compressive and flexural strengths. Mixtures that have high SP content yielded high compressive and flexural strength. This can be attributed to slight bleeding but further investigation is suggested to confirm this phenomenon.

This research is successful in deriving the optimum design mix (water, cement, and SP) of the self-compacting concrete. The derived optimum design mix yields passing marks for all rheological properties and have desirable compressive and flexural strength tests.

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