Modeling the Flexural Strength of Self-Compacting Concrete Based on Marble and Glass Powder Wastes by Employing the Methodology of Response Surface Analysis

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Abstract. Many researchers have studied the various properties of self-compacting concrete (SCC) with the addition of several types of powders, utilizing both traditional and statistical (mathematical) methods. The novelty of our research is to use the response surface methodology (RSM) to develop a mathematical model that forecasts and simulates the performance of the Flexural Strength tests of self-compacting concrete, Contains a quantity of marble and glass powders. The response surface methodology was utilized to create models for processes that encompassed three variables: the water-to-binder ratio, as well as the proportions of waste marble and glass powder. This methodology was utilized to gather a substantial amount of data and acquire the essential predictions for comprehending the studied phenomenon. Flexural strength tests were analyzed at intervals of 7, 28, and 90 days. Results indicate that the models employed in the flexural strength tests showed high statistical significance for 7 and 28 days (p-value < 0.01), and for 90 days, the models exhibit statistical significance (p-value < 0.05). The analysis of coefficients through the RSM approach validates its effectiveness as a predictive tool for evaluating the flexural strength tests of self-compacting concrete.

Keywords: Wastes; Self-Compacting Concrete (SCC); Marble Powder; Glass Powder; Flexural Strength; Response Surface Methodology (RSM).

1 Introduction

Self-compacting concrete (SCC) belongs to a category of concrete that requires no external energy for compaction [1]. It offers significant economic and technical advantages [2]. It's made with traditional concrete ingredients but includes superplasticizer additives for improved workability and sometimes viscosity-modifying additives [3]. This concrete (SCC) contains a relatively high amount of cement., besides cement, the paste content can be enhanced using fine fillers including silica fume, fly ash, marble powder, metakaolin, slag, and glass powder [4].

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Incorporation of wastes like glass and marble into concrete as aggregate substitutes can enhance flowability, strength, durability, and cost efficiency. Additionally, it promotes sustainable construction by improving concrete properties and reducing environmental impact and reducing greenhouse gases [5].

Response surface methodology (RSM) presents a highly efficient mathematical method utilized for predictions [6], this is employed to gauge the impact of independent variables on results through the execution of a few experiments [7, 8].

The RSM has been employed by numerous researchers for prediction purposes such as forecasting the characteristics of self-compacting concrete with about 95% similarity to experimental results [9], this confirms the effectiveness of the mathematical model in precisely estimating the attributes of new mixtures [8].

Our research work is part of the context of exploiting local materials including mineral additives, recycling local waste as a binder powder capable of replacing ordinary cement, and the goal is to develop resistant self-compacting concrete that is environmentally sustainable and cost-effective. And the research applies mathematical modeling to make a prediction about effects of adding marble and glass powder to self-compacting concrete (SCC), with a specific focus on flexural strength.

The research also introduces a precise model for evaluating the Flexural Strength tests of these concrete compositions, considering the importance of the models and the various parameters for the response using an analysis of variance (ANOVA) [10].

2 Materials and Methods

2.1 Used Materials

The concrete blend comprised Portland cement with mineral wastes (marble and glass), gravel, sand, and superplasticizer. The CEM II/B-L 42.5 N Portland cement, obtained from Lafarge Cement Algeria in compliance with NF EN 197-1 [11], possessed specific characteristics including a fineness rating of 3917 m^2/kg, a 28-day compressive strength of 46.25 MPa, and its density is estimated at 3050 kg/m^3.

In this study, two types of waste were used: marble waste powder, which was exported from the National Marble Company located in the city of Skikda, Algeria, and which had a specific surface area of 4363 m^2/kg and a specific density of 2720 kg/m^3.

In addition, the waste glass powder was supplied by COMAVER (an artistic glass manufacturing company) located in the city of Ghardaia, Algeria, and has a specific surface area of about 3260 m^2/kg with a specific density of 2485 kg/m^3.

Both the marble and glass powders were meticulously pulverized and sifted using an 80 μm sieve. The chemical properties of these powders, as well as the cement, are detailed in (Table 1).

Table 1. Chemical properties of cement, marble powder, and glass powder.

Chemical compositions (%)	Cement	Glass Powder	Marble Powder
Na_2O	-	14.7	-
MgO	1.94	1.3	1.95
Al_2O_3	3.55	2.13	0.2
SiO_2	15	68.1	0.462
P_2O_5	0.751	0.893	0.593
SO_3	3.43	0.213	0.593
Cl	0.0559	0.0298	0.0361
K_2O	0.707	0.213	0.0713
CaO	70.4	11.1	96.1
TiO_2	0.246	0.0784	-
MnO	0.0705	-	-
Fe_2O_3	3.66	0.345	0.213
CuO	-	0.0105	0.0257
SrO	0.122	0.0097	0.0682
As_2O_3	-	0.196	-
ZrO_2	-	0.066	-
BaO	-	0.521	-

The study also encompassed sand sourced from Oued Messad in the city of Djelfa in Algeria. This sand exhibited a specific density of 2620 kg/m^3, along with a sand equivalent of 78% and a fineness modulus of 2.36. Furthermore, the study incorporated granular in sizes 3/8 mm and 8/12.5 mm from crushed gravel, with specific gravity of 2670 kg/m^3.

The admixture employed is a liquid type of Superplasticizer (SP) known by the industrial name GRANITEX MEDAFLOW30, which is designed to significantly reduce water content. Formulated from Polycarboxylates Ether, it has a density of 1.07 containing 30% dry extract.

2.2 Preparation of Concrete

The chosen formulation procedure follows an experimental approach that relies on the paste volume, where the dry composition of the concrete volume per cubic meter is obtained (equivalent to 1000 L) comprises the combined volumes of aggregates used and cement paste [12]. This is expressed as the total amount of cement (C), the amount of gravel (G), the amount of sand (S), the amount of air (A), the amount of water (E) and the amount of superplastic (Sp), for a total of 1000 liters. Additionally, a ratio of gravel to sand (G/S) of 1 is maintained, and the binder dosage (cement + additions) is set at 400 kg/m^3.

Several lab experiments were conducted in mixture 1 to find the best mix for self-compacting concrete (SCC). Additionally, the superplasticizer (Sp) ratio was iteratively adjusted till a consistent amount was achieved, ensuring the key properties of the Combinations utilized in all the study. This process was guided by four main points: Flow and filling capability, segregation resilience, and viscosity [13].

The appropriate mix proportions were established and standardized for all subsequent mixtures to be poured into nine prisms with dimensions of 70 × 70 × 280 mm^3 for each concrete mixture.

These samples were immersed in water until the testing days.

2.3 Experimental Methods

By applying a load to a bending moment through upper and lower rollers on prismatic specimens, the maximum load sustained is recorded to calculate the flexural strength (see Fig. 1).

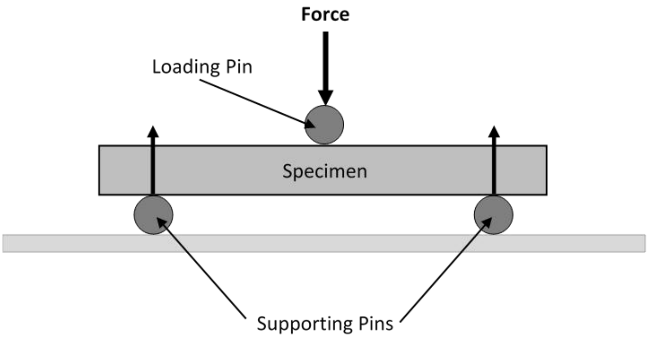


Fig. 1. 3-point Flexure Test

Flexural strength [14] was measured using a hydraulic press according to the EN 12390-4 standard. Flexural strength tests were performed following 7, 28, and 90 days with water curing.

2.4 Mathematical and Statistical Modelling

Response surface methodology or response surface modeling (RSM) is used to analyze, understand and improve the relationships between influencing factors because they are complex and concurrent with each other [6].

Among the types of designs for response surfaces, central composite design (CCD) was used, as it particularly helps in creating a second-order (quadratic) model for the response variables and the reduction of needed experiment numbers to predict quadratic terms [7].

A central composite design was utilized for three independent variables. The selected variables, each with three levels, the proportions of water/binder, marble powder, and glass powder were included and taken in the order (W/B; 0.4–0.5), (% MP; 0–25%), and (% GP; 0–25%), (see Table 2).

Table 2: The coding levels and corresponding values (CCD model).

Factors	**Sign**	**Encoded values**		
		-1	**0**	**+1**
W/B	**X1**	0,4	0,45	0,5
MP (%)	**X2**	0	12,5	25
GP (%)	**X3**	0	12,5	25

The design of a k factor 3-level experiment in CCD necessitates 2k for both factorial points and axial points, and c represent the center points, where k represents the quantity of variables under study, 2k represents every possible set of encrypted values where x equals either +1 or -1, and c denotes center points (levels are adjusted to encrypted level 0).

The quantity of experiments was established based on Equation (1).

$$N = 2^{k} + 2k + c \tag{1}$$

The graphic depicts a 3D CCD layout for three independent variables (***k = 3***). (see Fig. 2) [8].

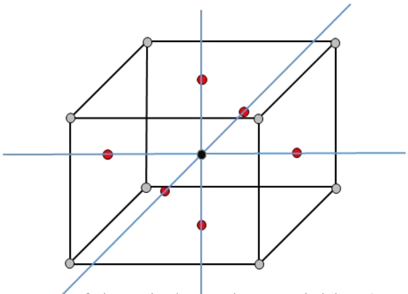


Fig. 2. A Layout of three independent variables (3D CCD).

The model employed took the form of a quadratic equation, to forecast the responses and demonstrate the connection between the independent variables, it is referred to by the second equation:

$$Y = B_0 + {}_{i}^{k} B_i X_i + {}_{i}^{k} B_{ii} X^2 + {}_{kj}^{k} B_{ij} X_i X_j + E \tag{2}$$

In this equation, Y signifies the functions that represent the response, B_0 represents the coefficient that remains constant, and B_i depicts the coefficients of the first-degree term, B_{ii} depicts the coefficients of the second-degree term, and B_{ij} depicts the coefficients of the interactive terms [14]. The model's significance was evaluated by analyzing the coefficient of determination (R^2), the adjusted (modified) coefficient (R^2 adj) and the p-value. To investigate the effect of factors on the flexural strength of specimens, a CCD was used to forecast their performance.

To conduct the experimental designs and statistical analyses, the JMP® Pro 14.0.0 program was used.

The specific composition of every combination is available and detailed within Table 3. The investigation included 17 mixtures.

Table 3. The proportion of components for 1 cubic meter of concrete

Mixtures	Pattern in (JMP)	Components								
		W/B	Binder			W	Sand	Gravel (3/8)	Gravel (8/16)	SP
			C	MP	GP					
Mix 1	−−−	0.4	400	0	0	160	908.04	303.84	621.66	8
Mix 2	−−+	0.4	320	0	80	160	908.04	303.84	621.66	8
Mix 3	−+−	0.4	320	80	0	160	908.04	303.84	621.66	8
Mix 4	−++	0.4	240	80	80	160	908.04	303.84	621.66	8
Mix 5	+−−	0.5	400	0	0	200	856.04	286.44	586.06	8
Mix 6	+−+	0.5	320	0	80	200	856.04	286.44	586.06	8
Mix 7	++−	0.5	320	80	0	200	856.04	286.44	586.06	8
Mix 8	+++	0.5	240	80	80	200	856.04	286.44	586.06	8
Mix 9	**a00**	0.4	320	40	40	160	908.04	303.84	621.66	8
Mix 10	**A00**	0.5	320	40	40	200	856.04	286.44	586.06	8
Mix 11	**0a0**	0.45	360	0	40	180	882.04	295.14	603.86	8
Mix 12	**0A0**	0.45	280	80	40	180	882.04	295.14	603.86	8
Mix 13	**00a**	0.45	360	40	0	180	882.04	295.14	603.86	8
Mix 14	**00A**	0.45	280	40	80	180	882.04	295.14	603.86	8
Mix 15	**000**	0.45	320	40	40	180	882.04	295.14	603.86	8
Mix 16	**000**	0.45	320	40	40	180	882.04	295.14	603.86	8
Mix 17	**000**	0.45	320	40	40	180	882.04	295.14	603.86	8

C: Cement, W: Water, B: Binder (Binder = Cement + GP + MP).
(A and +): The maximum value of the substance.
(a and −): The lowest value of the substance.
0: The middle value of the substance.

3 Results and Discussion

In the course of this study, the Flexural Strength of each concrete mixture was evaluated at the times to be studied (7, 28 and 90 days) using specimens that had been previously placed in water.

The specimens were used on the day they were to be tested.

3.1 Modeling of Flexural Strength Tests

We computed the coefficients of determination (R2) with adjusted coefficients (R2 adj) to evaluate the model's appropriateness and suitability.

These results show that the statistical equations accurately capture the true relationship between the independent variables and responses.

$$R^2 = 1 - \frac{\text{SSres (squared sum residuals)}}{\text{SStot (squared sum total)}} \quad (3)$$

$$\text{adj } R^2 = 1 - (1 - R^2)\,\frac{(n-1)}{n-1-p} \quad (4)$$

(n: quantity of samples)

(p: quantity of features)

The results demonstrate robust connections between the expected and empirical models.

According to CCD, the study sought to evaluate the effect of process variables on the flexural strength properties (hardening properties) of self-compacting concrete. The aim was to make predictions based on the values of different parameters, as outlined in (see Fig. 3 and Table 4).

Fig. 3. Flexural strength tests.

Table 4. The empirical findings and the forecasted values for the Flexural strength tests based on (RSM).

Mixtures	Flexural Strength (MPa)					
	(7 Day)		(28 Day)		(90 Day)	
	Empirical	Forecasted	Empirical	Forecasted	Empirical	Forecasted
Mix 1	2.498	2.451	2.574	2.610	2.631	2.810
Mix 2	1.668	1.742	1.875	1.922	2.12	2.105
Mix 3	2.034	2.085	2.565	2.554	2.627	2.559
Mix 4	1.258	1.250	1.681	1.725	1.734	1.913
Mix 5	1.601	1.610	2.084	2.056	2.61	2.437
Mix 6	1.475	1.426	1.827	1.854	1.827	1.902
Mix 7	1.559	1.487	1.824	1.793	1.993	2.014
Mix 8	1.129	1.177	1.471	1.451	1.711	1.538
Mix 9	2.017	1.947	2.384	2.268	2.732	2.456
Mix 10	1.426	1.490	1.802	1.854	1.833	2.082
Mix 11	1.612	1.625	2.051	1.969	2.302	2.235
Mix 12	1.335	1.317	1.723	1.740	1.887	1.927
Mix 13	1.691	1.750	2.05	2.084	2.2	2.240
Mix 14	1.306	1.241	1.668	1.569	1.716	1.649
Mix 15	1.512	1.516	1.801	1.873	2.017	2.0675
Mix 16	1.492	1.516	1.781	1.873	1.995	2.0675
Mix 17	1.532	1.516	1.908	1.873	2.137	2.0675

The information collected from CCD experiments was utilized to represent the responses by developing a mathematical equation that allows for the forecasting of the flexural strength for the times (7, 28, and 90 days), as specified below.

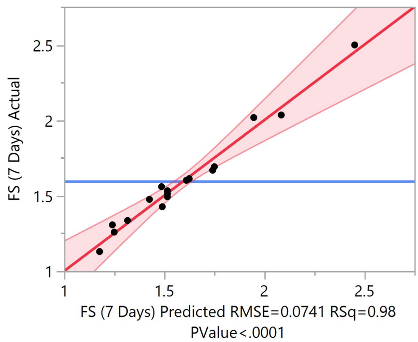
$$Y_{FS\,(7.days)} = 1.5158 - 0.2285\,X_1 - 0.1539\,X_2 - 0.2547\,X_3 + 0.0608\,X_1X_2 + 0.1313\,X_1X_3 - 0.0313\,X_2X_3 + 0.2029\,X_1^2 - 0.0451\,X_2^2 - 0.0201\,X_3^2 \quad (5)$$

$$Y_{FS\,(28\,days)} = 1.8731 - 0.2071\,X_1 - 0.1147\,X_2 - 0.2575\,X_3 - 0.0516\,X_1X_2 + 0.1216\,X_1X_3 - 0.0351\,X_2X_3 + 0.1875\,X_1^2 - 0.0184\,X_2^2 - 0.0464\,X_3^2 \quad (6)$$

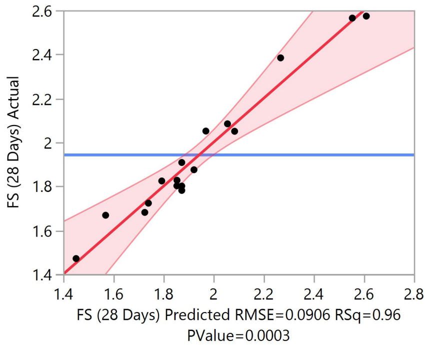
$$Y_{FS\,(90\,days)} = 2.0675 - 0.1870\,X_1 - 0.1538\,X_2 - 0.2953\,X_3 - 0.0429\,X_1X_2 + 0.0423\,X_1X_3 + 0.0149\,X_2X_3 + 0.2017\,X_1^2 + 0.0137\,X_2^2 - 0.1228\,X_3^2 \quad (7)$$

3.2 Analysis of Flexural strength Tests

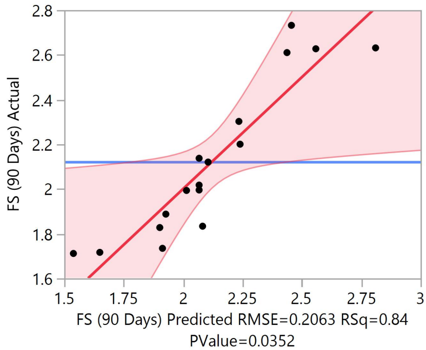
The ISO response curves and response surfaces were utilized to determine the optimal ratios for Flexural strength for the times (7, 28, and 90 days), in relation to water-to-binder (W/B), marble and glass powder (MP and GP), the coefficients demonstrate high values (see Fig. 4).



(A)



(B)



(C)

Fig. 4. The associations between the forecasted and actual values for the Flexural Strength tests are evaluated at three distinct time intervals: (A) 7 days; (B) 28 days; and (C) 90 days.

The model's statistical analysis of variance (ANOVA) was generated by using the JMP® Pro program. The significance was assessed by studying p-values (0.05 and 0.01), and detailed in below (see Table 5).

The ANOVA findings for the Flexural strength models at 7 and 28 days revealed a p-value of less than 0.01, achieving a high degree of statistical significance. Notably, for 90 days, the p-value was below 0.05, indicating the statistical significance of the models. It's important to note that for Flexural strength at 7 and 28 days, all parameters that are linear showed significant statistical importance. However, for Flexural strength at 90 days, only the (X_2) parameter did not exhibit statistical significance (p-value > 0.05). Regarding mutual interactions, a high statistically significant coefficient (X_1X_3) was observed at 7 and 28 days, while no statistical significance was observed for the mutual interactions at 90 days. In terms of the quadratic term coefficient, (X_1^2) and (X_1^2) showed a very strong statistically significant impact on the 7-day test (p-value < 0.01). At 28 days, only one coefficient (X_1^2) demonstrated a highly statistically significant effect, and no coefficient at 90 days showed statistical significance.

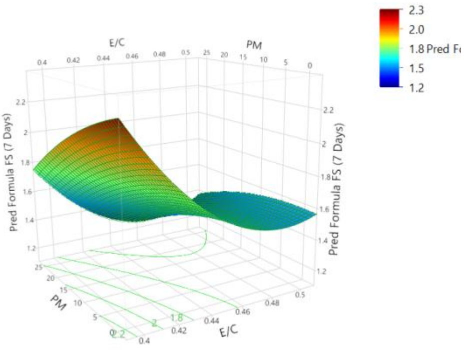
Table 5: Experimental results source includes the statistical data from the complete regression models and analysis of variance (ANOVA).

	DF	FS at 7 days		FS at 28 days		FS at 90 days	
		Ss	Prob > F	Ss	Prob > F	Ss	Prob > F
Model	9	1.710	0.0001*	1.480	0.0003*	1.619	0.0352*
X_1	1	0.522	0.0001*	0.429	0.0002*	0.350	0.0241*
X_2	1	0.237	0.0003*	0.132	0.0052*	0.237	0.0505
X_3	1	0.649	0.0001*	0.663	0.0001*	0.872	0.0027*
$X_1 X_{.2}$	1	0.029	0.0534	0.021	0.1510	0.015	0.5751
$X_1 X_{.3}$	1	0.138	0.0015*	0.118	0.0067*	0.0143	0.5794
$X_2 X_{.3}$	1	0.008	0.2716	0.010	0.3090	0.0018	0.8442
$X_1{}^2$	1	0.110	0.0029*	0.094	0.0116*	0.110	0.1536
$X_2{}^2$	1	0.005	0.3521	0.0009	0.7483	0.0005	0.9167
$X_3{}^2$	1	0.522	0.0001*	0.0058	0.4288	0.0404	0.3621
Residual	7	0.038		0.057		0.298	
Lack of Fit	5	0.038	0.0513	0.048	0.3579	0.286	0.0952
Pure Error	2	0.001		0.009		0.012	
R^2		0.978		0.963		0.845	
R^2 **adj**		0.950		0.915		0.645	
Adeq pre RMSE		0.074		0.091		0.206	
Cor Total	16	1.749		1.538		1.917	

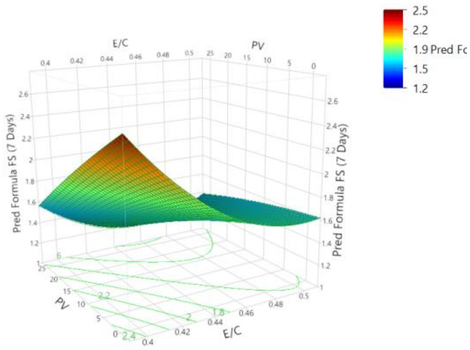
Ss: Sum of squares, *: value < 0.05

Upon reviewing (**Fig. 5A**, **Fig. 6A**, and **Fig. 7A**), we can visually examine the 3-D surface response plots illustrating the evolution of Flexural strength at all times (7, 28, and 90 days). Throughout this process, the E/B ratio ranged from 0.4 to 0.5, as the MP fluctuated between 0 and 25%, and we fixed at 12.5% the GP variant. The projected values were 1.8, 2.0, and 2.3 MPa, respectively. However, when E/B ratio ranged ranging from 0.4 to 0.5, with GP fluctuated 0 and 25%, while MP set at 12.5% (**Fig. 5B**, **Fig. 6B**, and **Fig. 7B**), the projections were 1.9, 2.2, and 2.2 MPa, in the same order.

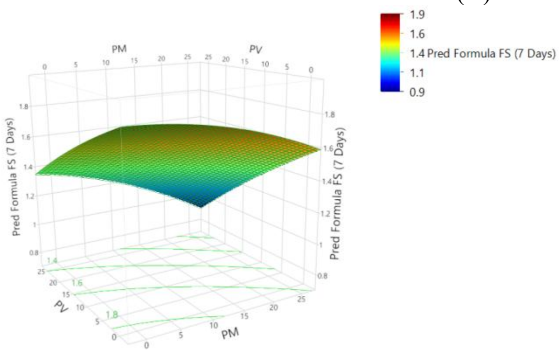
Moreover, when we adjusted between 0 and 25% the two variants (MP and GP), while we fixed at 0.45 the E/B Ratio, Flexural strength saw a decrease to 1.4, 1.7, and 1.9 MPa, respectively (**Fig. 5C**, **Fig. 6C**, and **Fig. 7C**).



(**A**)

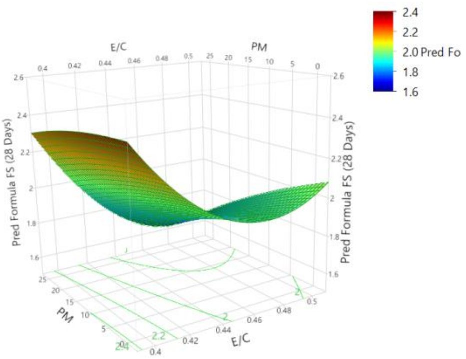


(**B**)

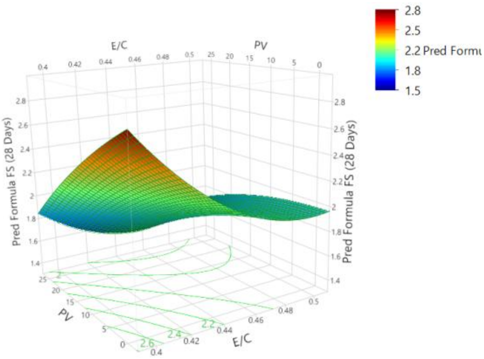


(**C**)

Fig. 5. The surface response plot showing the Flexural strength at 7 days, as per Response Surface Methodology (RSM), is as follows: (**A**) Dependent on (MP, W/B) / (**B**) Dependent on (GP, W/B) / (**C**) Dependent on (MP, GP).



(**A**)



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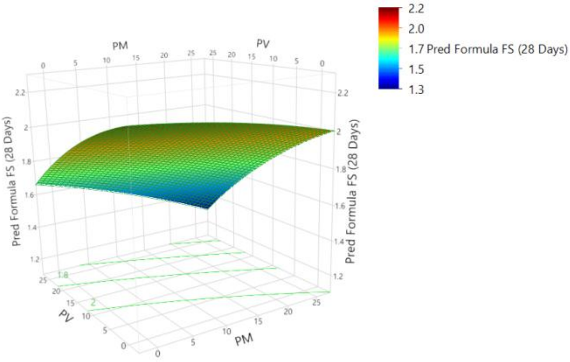
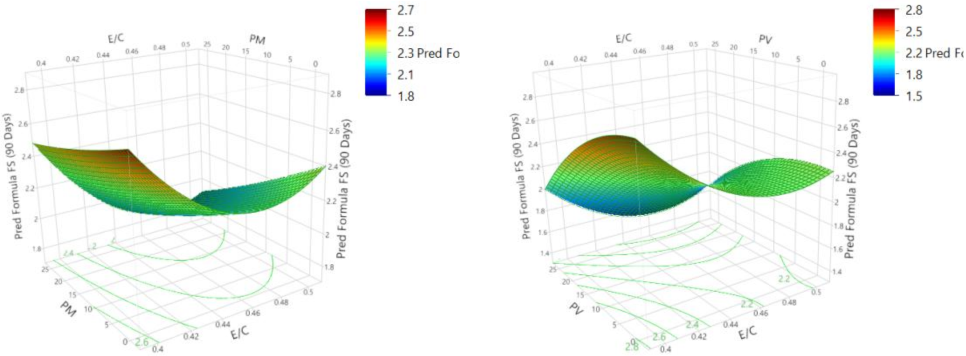
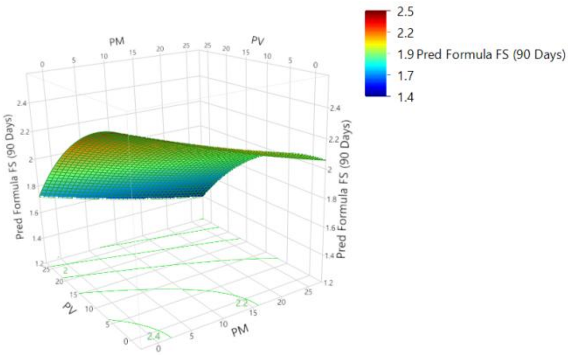


(**C**)

Fig. 6. The surface response plot showing the Flexural strength at 28 days, as per Response Surface Methodology (RSM), is as follows: (A) Dependent on (MP, W/B) / (B) Dependent on (GP, W/B) / (C) Dependent on (MP, GP).



(**A**) (**B**)



(**C**)

Fig. 7. The surface response plot showing the Flexural strength at 90 days, as per Response Surface Methodology (RSM), is as follows: (A) Dependent on (MP, W/B) / (B) Dependent on (GP, W/B) / (C) Dependent on (MP, GP).

4 Conclusions

The investigation aims to explore the effects of cement plus wasted marble and glass powder on the flexural strength of self-compacting concrete, utilizing the methodology of response surface (RSM). The research produced these significant results:

- The results of ANOVA show that the models we studied for Flexural Strength during the 7 and 90 day tests were statistically significant ($p\text{-value} < 0.05$). But the Flexural strength tests at (7 and 28-day), displayed a notably significant level of statistical importance (The p-value is less than 0.01).
- The RSM method's analysis of coefficients substantiates its effectiveness as a predictive tool for evaluation the flexural strength tests of SSC.
- The study centered on investigating the flexural strength tests of SSC utilizing three variants.
- We experimented with varying quantities, between 0 and 25 percent for both powders beneath investigation to forecast the results. Furthermore, we utilized the RSM to gather a greater quantity of data and predictions, while also decreasing the quantity of experiment mixtures needed.
- This approach has also shown its predictive effectiveness, as indicated by the calculation of coefficients (R2) and p-values.
- Subsequent research could focus on analyzing and predicting the durability properties of SCC.

5 References

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