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RESEARCH ARTICLE

Prediction of Compressive Strength of Silica Fume Blended High Strength Concrete Using Response Surface Methodology Approach

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Abstract

Objectives: In this study, a model was developed to predict the compressive strength of High Strength Concrete (HSC) mixed with silica fume using Response Surface Methodology (RSM). This study investigated the effects of cement, water, Silica Fume (SF), Coarse Aggregate (CA), and silica fume-cement ratio (SF/C) on the 28-day compressive strength of HSC. Silica fume is added with varying amounts of SF (5% to 25%) to cement content. **Methods:** Response surface methodology (RSM) was performed to investigate the influence of independent variables on the compressive strength of HSC. **Findings:** Analysis of the response surface plot reveals a remarkably low error percentage of less than 5%. This reveals a high degree of confidence (95%) in the model's accuracy. This study yielded a coefficient of determination (R^2) of 0. 9968. It is observed negligible deviation between predicted and actual 28-day compressive strength values, indicating high model accuracy. **Novelty:** The predicted equation is reasonably predicting the compressive strength of high strength concrete.

Keywords: High strength concrete; Response surface methodology; Silica fume; Compressive strength; Prediction model

1 Introduction

An important indicator of the mechanical properties of concrete is concrete compressive strength (CS). Also, the first step in concrete mix ratio design planning is the calculation of CS. Various studies have contributed to predictive models of CS. Meng et al.[1] showed that CS is most affected by the water-cement ratio (W/C) and is proportional to the decrease in W/C. Nakata et al.[2] stated that the strength of concrete is affected by the water-cement ratio and densification. In the literature[3–5], among the factors affecting CS, the volume content of W/C and coarse aggregate (CA) is considered to be the most important. Furthermore, Guo et al.[6] reported that CS shows not only a linear decreasing relationship with his W/C but also a non-linear relationship with CA characteristics Feldsian et al.[7] used response surface methodology to study the influence of ultrafine fly ash, silica fume, and sand as three main components on the workability and compressive strength of ultrahigh performance concrete. Zhang et al.[8] used RSM to build a Box-Behnken model to study the effects of different concentrations of silica fume, fly ash, and carbon fibers on the compressive strength and strain sensitivity coefficient of reactive powder concrete. Statistical RSM analysis was performed to obtain the optimal composition of the components and investigate the influence of the components on the 28-day compressive strength.

In recent years, the use of silica fume in high strength concrete has gained considerable attention due to its ability to enhance the mechanical properties of the concrete[9]. Tests conducted by Chan et al. have shown that the addition of silica fume in concretes such as HPC/HSC increased the residual compressive strength and durability of the concrete[10]. In this study, high strength concrete (HSC) of M60 to M80 grades according to IS 456:2000[11] and IS10262:2019[12] was produced. Compressive strength test was conducted on the cubical specimens for all the mixes after 28 days of curing as per IS 516 (2021)[13].

This study further supports these findings and provides a model for predicting the compressive strength of HSC mixed with silica fume. The response surface method is a powerful statistical technique used for optimizing and analyzing complex systems with multiple parameters. It allows researchers to identify the optimal combination of variables that will yield the desired outcome, in this case, high strength concrete using silica fume. By using RSM, researchers can reduce the number of experiments required to evaluate the effects and interactions of various parameters, such as the amount of silica fume, water-cement ratio, and curing time, on the strength of the concrete. This approach ensures that the concrete mixture is efficiently designed and that the desired compressive strength is achieved. Source: The response surface method has been successfully used in many scientific studies to optimize various parameters for different operations. Response surface methodology is a statistical and mathematical procedure used for optimizing and evolving problems where outcome variables are influenced by multiple influencing variables[14]. The response surface method allows for easy identification of relationships between a set of independent variables and is successfully applied where dependent parameters are strongly influenced by a set of parameters[15]. Design of experiment (DoE) is a systematic statistical framework for investigating the relationships between independent variables (factors) and their influence on a measured response (output) within an experiment[16].

The model developed in this study can be used to accurately predict the compressive strength of high strength concrete mixed with silica fume. The study conducted a comprehensive analysis of the effects of various factors such as cement, water, silica fume, coarse aggregate, and silica fume-cement ratio on the compressive strength of HSC.

2 Methodology

2.1 Materials and Methods

In this study, grade OPC 53 cement was used. SF was used as supplementary cementitious material (SCM) with different levels of addition. Coarse aggregates with a maximum size of 10 mm and natural river sand in a ratio of 67:33 were used. Specific gravity of cement, SF, 10mm and river sand are 3.15, 2.2, 2.6 and 2.6 respectively.

2.2 Response Surface Method

In this study, independent variables were Cement, Water, Silica fume (SF), Coarse aggregate (CA) and silica fume-Cement ratio (SF/C). The calculated response variable was 28-day compressive strength (CS). A comprehensive statistical framework incorporating regression analysis, response surface analysis, and residual plot analysis was employed in this study to investigate the main effects of the variables and their potential interactions.

3 Results and Discussion

A polynomial model was employed to fit the experimental CS data for the materials water, CA, SF/C, silica fume, and cement. The response surface model exhibiting optimal fit is expressed by the following equation:

CS = 76.8 + 9.4 Cement - 38 SF - 4.971 Water + 31 SF/C - 0.01 Cement*Cement - 19.5 SF*SF + 0.57 Water*Water - 21.5 SF/C*SF/C - 11.1 CA*CA + 7.0 Cement*SF + 2.76 Cement*Water + 37 SF*SF/C + 2.28 Water*SF/C.

Table 1 presents expected and empirical measurements of CS accompanied by residual error. Analysis of the response surface plot reveals a remarkably low error rate of less than 5% which indicates a high degree of confidence (95%) in the model's accuracy.

Table 1. Experimental and Predicted compressive strength values

Cement	SF	Water	SF/C	CA	Experimental CS value	Predicted CS value	Residual CS value
450	22.5	130	0.05	1151.736	82.55	82.2601	0.28988
450	45	130	0.1	1134.689	85.89	86.1241	-0.23406
450	67.5	130	0.15	1117.642	88.18	87.1753	1.00468
450	90	130	0.2	1100.595	84.42	85.4139	-0.99390
450	112.5	130	0.25	1083.548	81.61	80.8398	0.77019
450	22.5	140	0.05	1135.356	79.88	79.8156	0.06435
450	45	140	0.1	1118.309	82.24	83.6208	-1.38083
450	67.5	140	0.15	1101.262	85.54	84.6133	0.92667
450	90	140	0.2	1084.215	81.8	82.7932	-0.99316
450	112.5	140	0.25	1067.168	78	78.1603	-0.16031
450	22.5	150	0.05	1118.976	77.2	77.0929	0.10708
450	45	150	0.1	1101.929	79.58	80.8393	-1.25934
450	67.5	150	0.15	1084.882	83.9	81.7731	2.12691
450	90	150	0.2	1067.835	78.17	79.8942	-1.72416
450	112.5	150	0.25	1050.788	75.39	75.2026	0.18745
450	22.5	160	0.05	1102.596	74.51	74.0919	0.41805
450	45	160	0.1	1085.549	76.92	77.7796	-0.85961
450	67.5	160	0.15	1068.502	80.26	78.6546	1.60540
450	90	160	0.2	1051.455	76.54	76.7169	-0.17691
450	112.5	160	0.25	1034.408	71.77	71.9666	-0.19655
400	20	130	0.05	1180.285	80.68	80.2909	0.38907
400	40	130	0.1	1165.132	83.07	83.9812	-0.91117
400	60	130	0.15	1149.979	86.4	84.9235	1.47646
400	80	130	0.2	1134.826	82.69	83.1180	-0.42802
400	100	130	0.25	1119.673	79.94	78.5646	1.37537
400	20	140	0.05	1163.905	77.93	77.3729	0.55712
400	40	140	0.1	1148.752	80.35	81.0952	-0.74519
400	60	140	0.15	1133.599	83.71	82.0696	1.64037
400	80	140	0.2	1118.446	79.02	80.2962	-1.27618
400	100	140	0.25	1103.293	76.28	75.7749	0.50513
400	20	150	0.05	1147.525	74.19	74.1766	0.01342
400	40	150	0.1	1132.372	77.63	77.9310	-0.30096
400	60	150	0.15	1117.219	80.02	78.9375	1.08253
400	80	150	0.2	1102.066	76.35	77.1961	-0.84610
400	100	150	0.25	1086.913	73.63	72.7068	0.92315
400	20	160	0.05	1131.145	70.44	70.7020	-0.26203
400	40	160	0.1	1115.992	73.91	74.4885	-0.57848
400	60	160	0.15	1100.839	76.32	75.5271	0.79294
400	80	160	0.2	1085.686	72.67	73.8178	-1.14776
400	100	160	0.25	1070.533	69.97	69.3606	0.60942
375	18.75	130	0.05	1194.56	78.61	78.6424	-0.03244
375	37.5	130	0.1	1180.354	81.02	82.2779	-1.25790
375	56.25	130	0.15	1166.148	84.38	83.1091	1.27091
375	75	130	0.2	1151.942	79.7	81.1360	-1.43602
375	93.75	130	0.25	1137.736	75.97	76.3587	-0.38869
375	18.75	140	0.05	1178.18	75.82	75.4876	0.33240
375	37.5	140	0.1	1163.974	78.27	79.2005	-0.93054
375	56.25	140	0.15	1149.768	81.66	80.1092	1.55078
375	75	140	0.2	1135.562	75.99	78.2136	-2.22364
375	93.75	140	0.25	1121.356	71.28	73.5138	-2.23379
375	18.75	150	0.05	1161.8	72.03	72.0545	-0.02451
375	37.5	150	0.1	1147.594	75.51	75.8449	-0.33493
375	56.25	150	0.15	1133.388	78.92	76.8311	2.08890

Continued on next page

Table 1 continued

375	75	150	0.2	1119.182	74.29	75.0130	-0.72300
375	93.75	150	0.25	1104.976	70.6	70.3906	0.20935
375	18.75	160	0.05	1145.42	68.24	68.3432	-0.10317
375	37.5	160	0.1	1131.214	71.75	72.2111	-0.46108
375	56.25	160	0.15	1117.008	74.19	73.2747	0.91527
375	75	160	0.2	1102.802	70.57	71.5341	-0.96412
375	93.75	160	0.25	1088.596	67.91	66.9892	0.92075
350	17.5	130	0.05	1208.835	76.42	76.5514	-0.13135
350	35	130	0.1	1195.576	79.87	80.1534	-0.28339
350	52.5	130	0.15	1182.317	81.26	80.8356	0.42440
350	70	130	0.2	1169.058	77.6	78.5980	-0.99797
350	87.5	130	0.25	1155.799	73.89	73.4405	0.44948
350	17.5	140	0.05	1192.455	73.59	73.1597	0.43028
350	35	140	0.1	1179.196	76.06	76.8847	-0.82466
350	52.5	140	0.15	1165.937	79.48	77.6898	1.79023
350	70	140	0.2	1152.678	75.85	75.5750	0.27496
350	87.5	140	0.25	1139.419	72.17	70.5405	1.62951
350	17.5	150	0.05	1176.075	69.75	69.4898	0.26016
350	35	150	0.1	1162.816	72.26	73.3377	-1.07768
350	52.5	150	0.15	1149.557	75.71	74.2657	1.44431
350	70	150	0.2	1136.298	71.1	72.2739	-1.17386
350	87.5	150	0.25	1123.039	67.45	67.3622	0.08779
350	17.5	160	0.05	1159.695	65.9	65.5417	0.35829
350	35	160	0.1	1146.436	68.45	69.5125	-1.06245
350	52.5	160	0.15	1133.177	71.93	70.5634	1.36664
350	70	160	0.2	1119.918	67.35	68.6944	-1.34443
350	87.5	160	0.25	1106.659	63.72	63.9057	-0.18568

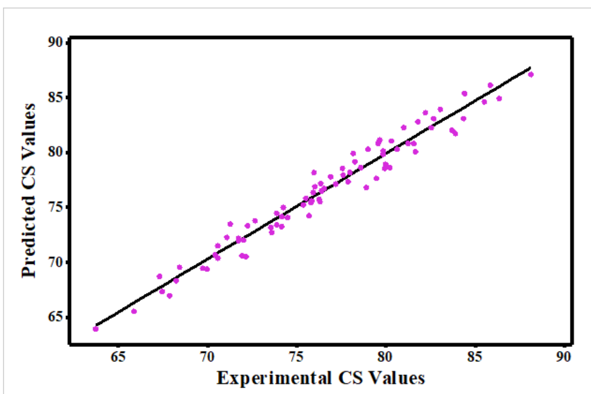

Fig 1. Scatter plot between actual and predicted values of CS

Figure 1 compares the actual and predicted values of CS along with residual error. Figure 1 shows a strong correlation between the experimental and predicted CS values, with a coefficient of determination (R-squared) of 0.9968. This indicates that the mathematical model is doing a good job of predicting the strength of the concrete mix[17–24].

The response surface analysis yielded a regression model comprising the variables "CS" plotted against "Cement", "Water", "Silica fume", "CA" and "SF/C" as depicted in Figure 2.

Figure 2 plot features a curved, saddle-shaped surface, suggesting a complex relationship between the two independent variables (SF/C and cement) and the response variable (compressive strength). There appears to be a general increase in compressive strength as the addition of silica fume percentage increases, up to a certain point i.e. at 15%. This is likely due to the pozzolanic activity of silica fume, which contributes to additional binding gel formation and improved strength. However, the plot also shows that exceeding this optimal silica fume level can lead to a decrease in compressive strength. This could be

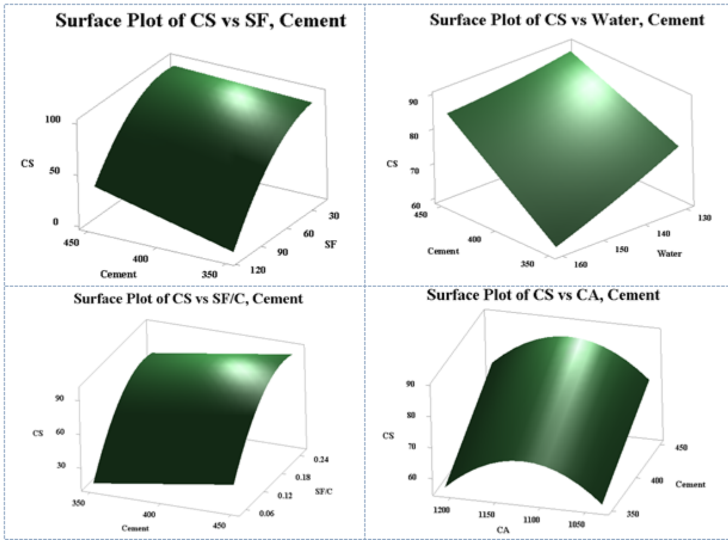

Fig 2. Response surface plots for "Cement", "Water", "Silica fume", "CA" and "SF/C" Vs CS

due to factors like excessive water absorption by silica fume or interference with hydration processes. RSM provides a valuable tool for investigating these relationships between the two independent variables and identifying optimal combinations of these factors.

The influence of various factors (Cement, SF, Water, CA and SF/C) on compressive strength (CS) was investigated in this study. Their influence on the CS was observed by the slope's magnitude. The absolute value of the slope served as a direct measure of the influence on CS, with steeper slopes signifying greater impact and shallower slopes signifying weaker effects. The present study observed a relation between the gradient of the plot displaying the combined influence of cement, SF, water, CA, and SF/C on CS and the material's compressive strength. It was noted that the CS increased with an increase in the percentage of silica fume from 5 to 25%. The study yielded a coefficient of determination value (R^2) of 0.9968. Compared to the combined effect of other mix components, silica fume had a much greater impact on CS growth over time, as evident in the steeper slope of the CS vs. age plot in Figure 3.

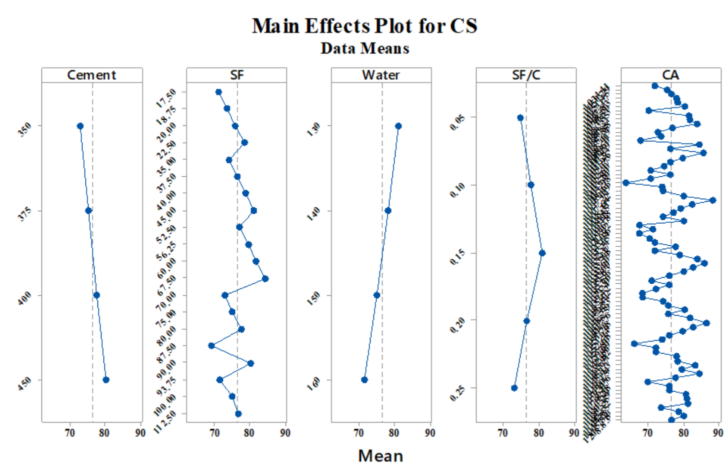

Fig 3. Main effects plot for CS

4 Conclusion

The following conclusions are drawn based on the present investigation.

1. Analysis of the response surface plot reveals a remarkably low error percentage of less than 5%. This reveals a high degree of confidence (95%) in the model's accuracy.
2. The study yielded a coefficient of determination value (R^2 of 0 9968).
3. Statistical analysis of the regression model reveals negligible deviation between predicted and actual 28-day compressive strength values, indicating high model accuracy.
4. RSM provides a valuable tool for investigating these relationships between the two independent variables and identifying optimal combinations of these factors.
5. The present model predicts the 28-day strength of high strength concrete using silica fume reasonably so that the experimental trials can be minimized.

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