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Predictive Models and Optimization of Strengths and Durability of Self-Compacting Concrete Admixed with Styrofoam

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ORIGINAL RESEARCH

Abstract— Shredded Styrofoam beds are often discarded in port regions and have also been utilized as protective packaging for electronic devices to avoid damage. Ensuring sustainability in engineering is incredibly important, as excessive use of construction materials contributes to the step-down of natural resources. The aim of this study is to examine the use of shredded Styrofoam beds to optimize and create prediction models regarding the strength and durability of self-consolidating SCC that incorporates fine aggregates and Styrofoam, employing the response surface method. The characteristics of SCC met the relevant standards. The optimal Styrofoam content was identified with fine aggregate replacement levels of 0, 0.1, 0.2, 0.3, and 0.4 %, utilizing 1:2.29:1.67 and 0.55 as a mix ratio and water-cement ratio respectively. A statistical analysis was performed on the laboratory experimental results using Design Expert software. Additionally, predictive models for the strength and durability of SCC incorporating Styrofoam were established. The findings indicated that the models demonstrated R^2 values of 89.37 %, 93.05 %, and 98.16 % for compressive strength, splitting tensile strength, and water absorption of the concrete, respectively. Moreover, the optimal parameters of 0.3 % Styrofoam content and a curing period of 28 days were determined, resulting in strength and durability metrics of 17.865 N/mm^2, 2.285 N/mm^2, and 0.75 % for compressive strength, splitting tensile strength, and water absorption of the concrete, respectively. Therefore, Styrofoam is suggested for use in the formation of lightweight SCC, and the developed models can be utilized to predict the strengths and durability of lightweight SCC using Styrofoam as a replacement for fine aggregate.

Keywords— Compressive Strength, Design Expert Software, Response Surface Methods, Self-Compacting Concrete, Styrofoam

1 INTRODUCTION

Self-compacting concrete is recognized as an emerging type of concrete due to its capacity to fill molds and achieve compaction solely through its own weight. SCC is a distinct variety of concrete with eminent water requirement; it can flow and set within a mold autonomously. In the construction industry, the adoption of SCC reduces the necessity for surface finishing to eliminate sand and mitigate noise at construction sites. (Sua-Iam and Makul (2015). Incorporating light aggregates in concrete formation can lessen the overall weight of the structures, thus enabling the use of smaller member sections and ultimately reducing total construction expenses.

In concrete production, river sand is utilized globally as a fine aggregate. Continuous extraction of sand from our rivers has led to the depletion of this natural resource. There is a pressing need to dig into sustainable options to river sand in the creation of self-compacting (SC) concrete, and one such alternative being examined in this research is Styrofoam. Styrofoam is a widely used plastic waste material, particularly prevalent in coastal areas. This waste, primarily ecosystems. Styrofoam will be used to partially replace generated by the packaging industry, contributes significantly to environmental pollution and poses risks to river sand in the development of SCC. Furthermore, this study will employ the response surface methodology (RSM) for optimization. Saddique and Anhad (2017) explored the strengths and microstructural properties of SCC containing metakaolin as a partial replacement for cement and rice husk ash as a partial replacement for fine aggregate. Their findings indicated that substituting metakaolin for cement and fine aggregates contributed to enhanced strength in SCC. Research by Ammar *et al.*, (2020) demonstrated that using EPS as a partial replacement for coarse aggregate, along with varying percentages of waste plastic fiber in SC concrete, resulted in improved characteristics of SC lightweight concrete (SCLWC). Both compressive and flexural strengths were found to increase with the increasing percentage of waste plastic fiber (WPF) in SCLWC, while UPV diminished with higher SCLWC ratios.

Research by Madandoust *et al.*, (2011) aappraised the initial characteristics of self-compacting light concrete incorporating expanded polystyrene (EPS). The results indicated that EPS can enhance slump flow retention by as much as 17 %. Furthermore, a nonlinear multiple regression analysis was employed to accurately predict slump flow according to hauling time. Sulaiman *et al.*, (2022) used sesame straw ash (SSA) as partial replacement for cement in concrete. The findings indicated that the maximum amount of SSA to be used should not exceed 10 % replacement in concrete production. Additionally, Garba *et al.*, (2024a) conducted a study focusing on creating predictive models and optimizing strength and durability of reinforced laterized concrete, which could be utilized to forecast the necessitated strength and durability of laterized concrete. Garba *et al.*, (2024b) investigated the optimization of incorporating cement kiln dust and established predictive models for the

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strength and durability of self-compacting concrete. The models created for all dependent variables are quartic with a strong correlation coefficient. The optimized results demonstrated 32.041 N/mm² and 3.455 N/mm² for compressive and flexural strength, respectively, at 10.683 % cement kiln dust, alongside a water absorption rate of 2.916 % at 20 % cement kiln dust content. It was concluded that up to 10 % of cement kiln dust could be used as a partial substitute for cement. Jae *et al*., (2024) developed predictive models and optimized the mechanical characteristics of kenaf-polypropylene fibre reinforced concrete using RSM. Bello *et al*., (2021) assessed the effects expanded polystyrene beads waste as a substitute for coarse aggregate in lightweight concrete.

This research employs response surface methods to examine the use of styrofoam as a partial substitute for fine aggregate and to develop models for predicting and optimizing the strengths and durability of SCC. The objective of this research is to integrate the laboratory data related to strength and durability properties into design expert software for analysis and result optimization

2 Material and Methods

2.1 Materials

2.1.1 Cement

Portland limestone cement (PLC) was utilized in this research. It has a specific gravity of 3.18. The physical characteristics of the cement were assessed to evaluate the quality of the cement utilized in the study.

2.1.2 Coarse Aggregate

The coarse aggregate utilized was granite with a maximum nominal particle size of 20 mm, obtained from the Abdu kwari quarry located across from the Nigeria College of Aviation Technology (NCAT) in Zaria. The aggregate was free from any moisture or debris. The bulk density of the aggregate was assessed and determined to be 1416 kg/m³. The aggregate impact value and crushing value were recorded at 28% and 24%, respectively.

2.1.3 Fine Aggregate

The fine aggregate used was sourced at area G behind ABU Zaria. The bulk density of the fine aggregate is 1290.5kg/m³.

2.1.4 Superplasticizer

In this study, the incorporation of superplasticizers is essential to ensuring the maintenance of self-consolidating mixtures. For this research, polycarboxylic ether (PCE) was utilized.

2.1.5 Water

The water utilised in this study was sourced from tank supplies provided by the Department of Civil Engineering.

2.1.6 Styrofoam

The styrofoam utilized in this research was obtained from a dealer of electronic materials located at Kwangila on Sokoto Road, Zaria, Kaduna State, and it was processed into various sizes at the Nigeria Leather Research Institute.

2.1.7 Design Expert Software

The response surface methodology utilized in this study was conducted using Design Expert version 13 (2021).

2.2 Methods

2.2.1 Compressive Strength

The compressive strength of hardened self-compacting concrete cubes with dimensions of 150x150x150mm was assessed after curing periods of 3, 7, 14, 21, and 28 days using a compressive testing machine located at the Civil Engineering department of Ahmadu Bello University, Zaria. This assessment was conducted in accordance with BS-EN-12390-3, 2019. The load at failure was documented, and the strength of each concrete cube was calculated using equation 1.

$$F_{C} = \frac{Failure\ load}{Area\ of\ the\ cube} \quad (1)$$

2.2.2 Split Tensile Strength

The splitting tensile strength test was conducted on a concrete cylinder specimen measuring 100mm x 300mm, following the BS-EN-12390-6(2023) standard testing procedure. The splitting tensile strength can be calculated using equation 2.

$$F_S = \frac{2p}{\pi LD} \quad (2)$$

Where P is the failure load, L is the height of the cylinder and D is the diameter of cylinder.

2.2.3 Water Absorption

A water absorption test was executed to assess how quickly concrete specimens can absorb or hold water. Concrete cubes were formed and cured using the immersion method for periods of 28, 56, and 90 days. This test was executed in compliance with BS-EN-206 (2013).

2.2.4 Response Surface Methodology (RSM)

Ravathi et al. (2018) explain the response surface method as a blend of statistical and mathematical approaches used for development and optimization efforts. This technique employs exploratory data gathered through scientific experimental design to perform regression analyses and create a practical connection among the influencing factors and the response variable (Jo et al., 2007). The equation below can illustrate a multinomial liason between the response variables and the independent variables (Montgomery, 2017).

$$Y = F_0 + \Sigma_{i=1}^{k} F_i N_i + \Sigma_{i=1}^{k} F_{ii} N_{ii}^2 + \Sigma_{j=2}^{k} \Sigma_{i\le i\le j}^{j=1} F_{ij} N_i N_j + \varepsilon \quad (3)$$

In this scenario, Y symbolizes the dependent variable, while ni and nj symbolize the independent variables (with i and j ranging from 1 to k). Fo indicates the constant coefficient, and Fi, Fii, and Fij correspond to the coefficients related to the linear, quadratic, and interaction effects, respectively, with ε denoting the defect term. The R^2 values, which have a range from 0 to 1, were used to assess the adequacy of the developed model. A greater R^2 value, nearing 1, reflects the precision and significant importance of the model, as cited by Montgomery (2017).

3 Results and Discussions

3.1 Compressive Strength

The SCC mix without Styrofoam achieved a peak strength of 20.10 N/mm² after curing for 28 days. Among the different percentages of Styrofoam used to replace fine aggregate, the replacement at 0.1% yielded a compressive strength of 19.80 N/mm², which was the closest to the control group's strength at 28 days. It was observed that higher Styrofoam replacement percentages resulted in a lessen in the strength, which is due to the voids introduced in the concrete matrix that impair the bond between aggregate particles. Moreover, this decline in

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strength can be related to Styrofoam's soft characteristics and the increased number of cavities present in the concrete, as indicated by the water absorption results. This finding is consistent with the research executed by Mochamad *et al*., (2019). Additionally, Fig. 1 demonstrates that the strength of the SCC with Styrofoam content increases as the curing period extends.

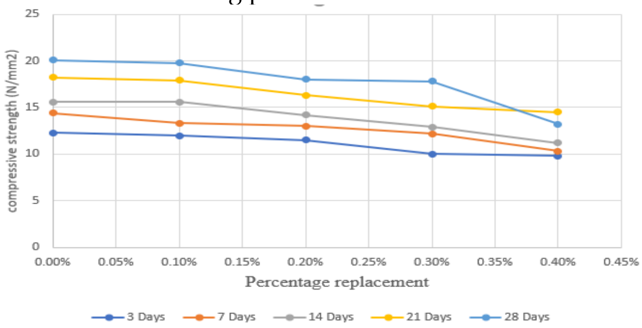

Fig. 1: Compressive Strength of SCC Versus Curing age

3.2 Splitting Tensile Strength

In Figure 2, it was observed that the split tensile strength of SCC diminishes as the proportion of fine aggregate substituted with styrofoam rises. The control mix, which does not contain any styrofoam, demonstrated a split tensile strength of 2.52 N/mm² after 28 days. Among the various mixes assessed for split tensile strength at 28 days, the one most similar to the control was the 0.1% replacement level, attaining a split tensile strength of 2.50 N/mm². In general, an increased amount of styrofoam in the concrete leads to a gradual decline in split tensile strength. Comparable results were found by Ubi *et al*., (2022).

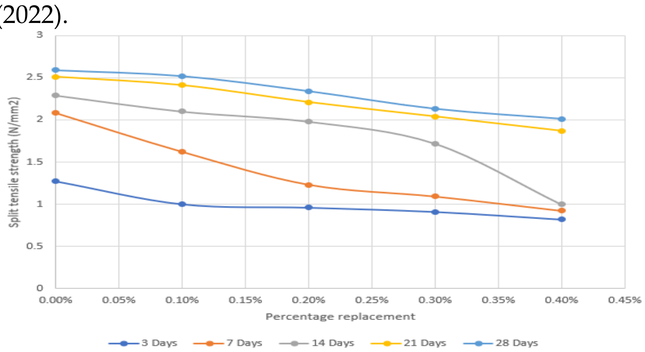

Fig. 2: Split Tensile Strength of SCC with Styrofoam content

3.3 Water Absorption

According to Figure 3, it was shown that replacing a higher percentage of fine aggregate with styrofoam improved the water absorption of the self-compacting concrete. The water absorption measurements for the control mix at 28, 58, and 90 days were recorded at 0.69%, 0.95%, and 1.01%, respectively. In contrast, with 0.3% Styrofoam replacement, the recorded water absorption values were 3.0%, 3.12%, and 3.20%. This indicates a general increase in water absorption in the concrete, which may be attributed to the creation of additional pores due to the extended immersion of the concrete in water, resulting in its enhanced absorption properties. Ranjbar and Mousavi (2015) noted that progressively replacing aggregates with EPS beads up to 30 % by volume resulted in enhanced slump flow and water absorption, although it decreased the compressive strength of SCC.

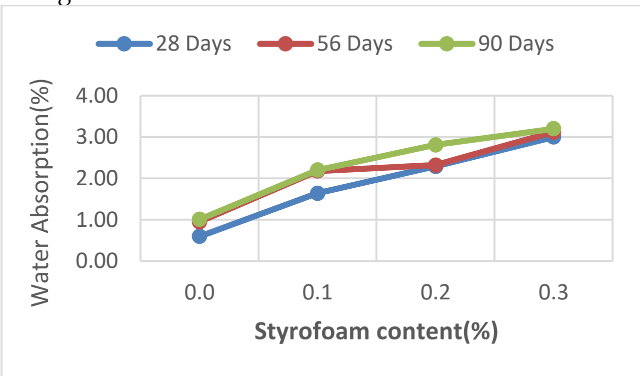

Fig. 3: Water absorption of SCC with Styrofoam Content

3.4 Analysis of Variance

One-way variance analysis (ANOVA) was used to evaluate whether the independent variables significantly affect the dependent variables. By adhering to a predetermined confidence level, the analysis of variance assessed the influence of significant parameters on the models. A confidence interval of 95% was employed, indicating that the P-value is below 5% (p-level < 0.05). Additionally, the analysis evaluated the lack of fit at the established significance level of the P-value. The outcomes of the ANOVA for strengths, and water absorption of SCC partially substituted with Styrofoam are presented in Tables 1, 2, and 3, respectively. The F-values found for the models are 73.95, 117.84, and 319.70 for compressive strength, split tensile strength, and water absorption, respectively, demonstrating that these models are significant. Furthermore, there is only a 0.01% probability that the F-value could arise due to random chance

Table 1. Analysis of Variance of Compressive Strength of SCC with Styrofoam

Source	Sum of Squares	Df	Mean Square	F-value	p-value	
Model	409.40	5	81.90	74.00	< 0.0001	Significant
S-styoryofoam Content	91.40	1	91.40	82.50	< 0.0001	
C_a-Curing Age	313.40	1	313.40	283.10	< 0.0001	

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SC_a	2.80	1	2.80	2.50	0.1193
S^2	1.32	1	1.32	1.20	0.2806
C_a^2	1.40	1	1.40	1.30	0.2672
Residual	48.71	44	1.11		
Lack of Fit	48.71	19	2.56		
Pure Error	0.0000	25	0.0000		
Cor Total	458.08	49			

Table 2: Analysis of Variance of Split Tensile Strength of SCC with Styrofoam

Source	Sum of Squares	Df	Mean Square	F-value	p-value	
Model	16.50	5	3.30	117.80	< 0.0001	Significant
$Styrofoam$ Content	3.50	1	3.50	125.30	< 0.0001	
C_a-Curing Age	11.96	1	12.00	427.70	< 0.0001	
SC_a	0.0232	1	0.0232	0.8290	0.3680	
S^2	0.0020	1	0.0020	0.0690	0.7940	
C_a^2	0.7300	1	0.7300	26.11	< 0.0001	
Residual	1.23	44	0.0280			
Lack of fit	1.23	19	0.0650			
Pure error	0.0000	25	0.0000			
Cor total	17.70	49				

Table 3: Analysis of Variance of water absorption of SCC with Styrofoam

Source	Sum of Squares	Df	Mean Square	F-value	p-value	
Model	24.70	5	4.90	319.70	< 0.0001	Significant
C_a-curing age	23.05	1	23.10	1494.50	< 0.0001	
S-Styrofoam	1.07	1	1.07	69.60	< 0.0001	
SC_a	0.1720	1	0.1720	11.20	0.0022	
C_a^2	0.6700	1	0.6700	43.44	< 0.0001	
S^2	0.0180	1	0.0180	1.18	0.2857	
Residual	0.3200	27	0.0120			
Lack of fit	0.3196	3	0.1065			
Pure error	0.0000	24	0.0000			
Cor total	25.12	35				

3.5 Regression Models

The regression equations for compressive strength, splitting tensile strength, and water absorption produced for the responses using the response surface approach are provided in equations 3, 4, and 5 based on the analysis of variance following the removal of the models' unimportant terms.

$$F_c = 11.22117 - 2.86961S + 0.393971C_a \quad (3)$$

$$F_s = 1.10654 - 2.28901S - 0.109486C_a - 0.001904 \quad (4)$$

$$W = -0.109616 + 0.063879S + -3.66010C_a + 0.024398\,SC_a - 0.000304S^2 + 2.25000C_a^2 \quad (5)$$

Where F_C, F_S and W represent the compressive strength, split tensile strength and water absorption of SCC.

The Compressive, split tensile, and water absorption 2D and 3D plots of the self-compacting concrete that partially substituted Styrofoam for fine aggregate are displayed in Figures 4, 5, and 6, respectively. The 2D plot showed that as the proportion of Styrofoam content grew, the compressive, split tensile, and water absorption strengths of the self-compacting concrete decreased, as seen by the change from the reddish to the blue zone.

The void areas that are formed inside the concrete matrix cause the strong link between the aggregate particles to weaken, which results in a drop in strength. When Styrofoam was used to partially substitute fine aggregate, Ranjbar and Mousavi (2015) obtained similar results and a similar pattern from the 3D plot.

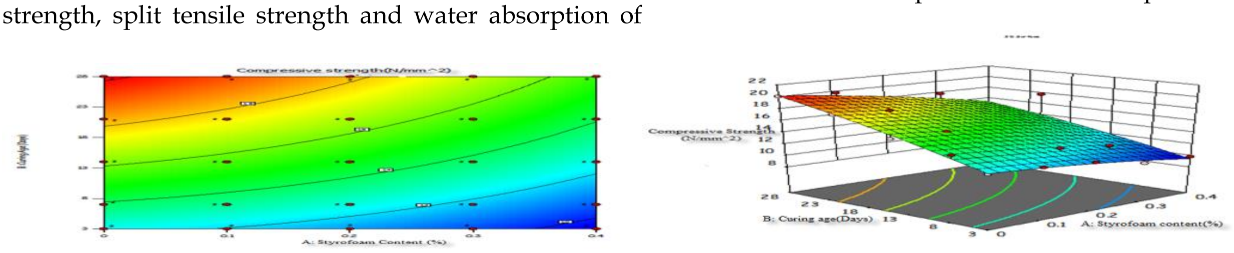

Fig. 4: 2D and 3D Contour plot of compressive strength of SCC with Styrofoam

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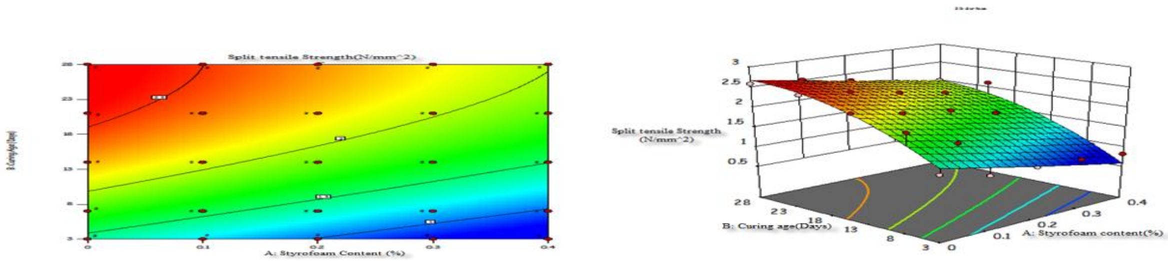

Fig. 5: 2D and 3D Contour plot of Split Tensile strength of SCC with Styrofoam

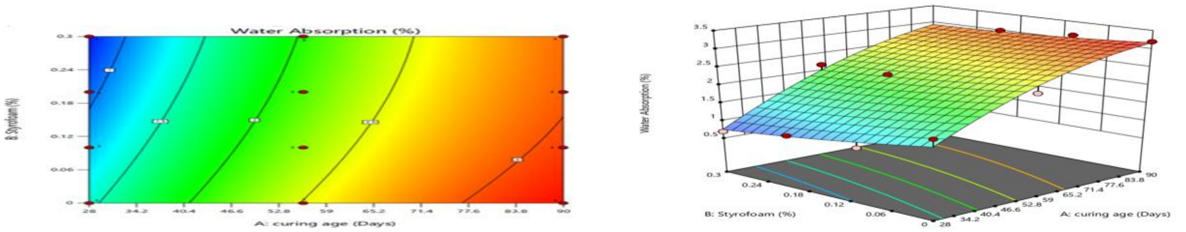

Fig. 6: 2D and 3D Contour plot of water absorption of SCC with Styrofoam

3.6 Coefficient of Determination of the Response

The produced response variable models with coefficients of determination with R2 values higher than 80% are displayed in Table 4. It is possible to correlate the models with experimental results on the compressive strength, split tensile strength, and water absorption of the SSC partially substituted fine aggregate with Styrofoam, which are 89.37%, 94.05%, and 98.16%, respectively.

All response variables were in good agreement, as evidenced by the difference between the adjusted and predicted R^2 values being less than 0.2. The acceptable desirability of responses, or adequate precision (AP) results, in Table 4 were also higher than 4. This showed that all of the models produced fit the water absorption and predicted strengths of SC concrete mixed with Styrofoam.

Table 4: Coefficients of Determination for the Response Investigated

Response	R^2	Adjusted R^2	Predicted R^2	Adequacy Precision AP
Compressive Strength of the SCC aggregate with Styrofoam, F_c	0.8937	0.8816	0.8509	25.4387
Split tensile Strength of the partially with Styrofoam, F_s	0.9305	0.9226	0.9070	36.2179
Water absorption, W	0.9816	0.9785	0.9723	47.8042

3.7 Optimization of SCC with Styrofoam

To maximize the potential of a system or design, optimization entails applying mathematical methods, models, and algorithms. Tables 5 and 6 display the optimization objective, constraint, and outcomes for water absorption, split tensile strength, and compressive strength. The water absorption value is 0.976, and the compressive and split tensile strength values are 0.849. The findings indicate that at 0.227 percent Styrofoam content and after 28 days of curing age, the compressive strength and split tensile strength are 17.865 N/mm² and 2.285 N/mm², respectively. The ideal water absorption value is 0.75 percent at 0.30 percent Styrofoam content after 28 days of curing.

Table 5: Optimization Goals and Constraints

Response	Symbol	Goal	Lower Limit	Upper Limit
Styrofoam content (%)	S	Maximize	0	0.40
Curing age(days)	C_a	3-28	3	28.00
Compressive Strength of SCC with Styrofoam(N/mm²)	F_c	Maximize	9.8	20.10
Split tensile strength of SCC concrete with Styrofoam(N/mm²)	F_s	Maximize	0.82	2.59
Water absorption (%)	W	Minimize	0.69	3.20

Table 6: Optimization Results of Strength (Compressive and Split tensile)

S/NO	Styrofoam Content (%)	Curing Age (Days)	Compressive Strength (N/mm^2)	Split Tensile Strength (N/mm^2)	Desirability	
1	**0.227**	**28.000**	**17.865**	**2.285**	**0.849**	**Selected**
2	0.226	28.000	17.882	2.288	0.849	
3	0.230	28.000	17.829	2.280	0.849	
4	0.224	28.000	17.901	2.290	0.849	
5	0.221	28.000	17.936	2.295	0.848	
6	0.234	28.000	17.784	2.275	0.848	
7	0.236	28.000	17.757	2.271	0.848	
8	0.217	28.000	17.983	2.301	0.848	
9	0.216	28.000	18.003	2.304	0.848	
10	0.214	28.000	18.022	2.306	0.848	
11	0.213	28.000	18.039	2.309	0.847	
12	0.243	28.000	17.668	2.259	0.847	
13	0.000	28.000	20.187	2.679	0.753	
14	0.022	28.000	20.005	2.639	0.736	

Table 7: Optimization Results of Water Absorption

S/NO	Curing age(Days)	Styrofoam (%)	Water Absorption (%)	Desirability	
1	**28.000**	**0.300**	**0.750**	**0.976**	**Selected**
2	28.000	0.297	0.760	0.970	
3	28.000	0.272	0.796	0.960	
4	28.000	0.260	0.821	0.950	
5	29.386	0.300	0.824	0.950	
6	28.000	0.213	0.910	0.910	
7	28.000	0.211	0.910	0.910	
8	28.000	0.120	1.120	0.830	
9	28.000	0.112	1.130	0.820	
10	28.000	0.090	1.200	0.800	

3.7 Conclusions

Based on the experimental study, the following conclusions were achieved:

i. All other correlation values above 80% demonstrate a significant association, with the compressive strength, split tensile strength, and water absorption having R2 values of 89.37%, 94.05%, and 98.16%, respectively.

ii. The water absorption was valuated to be 0.30 percent Styrofoam content at 28 days of curing age with a value of 0.75 percent, and the optimal values were found to be 0.27 percent Styrofoam content with compressive and split tensile strengths of 17.865 N/mm2 and 2.25 N/mm2 respectively.

iii. It was resolved that regression models may be used to forecast the water absorption, splitting tensile strength, and compressive strength of SCC mixed with polystyrene foam.

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