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Application of RSM in optimizing the density and strength of lightweight concrete using EPS solution

ABSTRACT

This work addresses the challenge of balancing low density and adequate strength in Lightweight Concrete (LWC) by proposing a novel approach using an Expanded Polystyrene (EPS) adhesive solution instead of conventional beads. This solution acts as both a lightweight agent and an auxiliary binder, effectively overcoming issues like buoyancy, segregation, and weak interfacial bonding. Incorporating the solution after cement paste formation ensured uniform dispersion and enhanced material homogeneity. Response Surface Methodology (RSM) was used to evaluate the interactive effects of W/C (water to cement mass ratio), S/C (sand to cement mass ratio), and EPS volume fraction on compressive strength and density. The optimization yielded a maximum desirability (D=1.000). The optimal mixture (W/C =0.46, S/C = 1.76, EPS = 38.65%) predicted a compressive strength of 10.64 MPa and a density of 939.2 kg/m^3. Experimental validation under rounded conditions (10.4 MPa and 935 kg/m^3) confirmed the model's reliability, demonstrating a successful balance suitable for non-load-bearing applications.

Keywords: *Lightweight concrete (LWC), EPS adhesive solution, RSM, CCD, density, compressive strength, mixture optimization.*

1. INTRODUCTION

Lightweight concrete (LWC) has gained increasing attention in construction due to its ability to reduce structural self-weight while providing improved thermal insulation, which is beneficial for energy-efficient buildings. These advantages can enhance structural performance, reduce foundation demands, and expand design flexibility. However, maintaining an appropriate balance between low density and adequate mechanical strength remains a significant challenge, particularly when polymeric lightweighting agents are used [1-4].Although these agents are effective in reducing density, they often weaken the cementitious matrix or interfacial bonding, leading to a noticeable reduction in mechanical performance and limiting the structural applicability of LWC. Conventional Expanded Polystyrene (EPS) beads are widely used as lightweight aggregates in concrete; however, their incorporation is associated with several inherent drawbacks. Due to their extremely low density, EPS beads tend to float during mixing and casting, leading to buoyancy-related segregation and nonuniform dispersion within the cementitious matrix. In addition, the smooth and hydrophobic surface of EPS results in weak interfacial bonding with the surrounding matrix, while the increased entrapped air and interconnected voids contribute to high overall porosity. These combined effects often cause a pronounced deterioration in mechanical properties, significantly restricting the structural performance and practical applicability of EPS-based lightweight concrete [4-6]. To address these limitations, the present study introduces a novel EPS-based adhesive polymer solution that replaces conventional EPS beads and functions simultaneously as a lightweighting agent and a secondary binding phase. Unlike traditional approaches, this solution is incorporated after the initial formation of the cement paste, which enables more uniform distribution throughout the matrix and minimizes issues related to buoyancy and segregation. The adhesive nature of the polymer enhances interfacial adhesion between the lightweight phase and the cementitious matrix, thereby improving structural continuity. Moreover, the controlled incorporation of the solution promotes the formation of stable micro-scale pores rather than large, irregular voids, leading to a more homogeneous pore structure. This approach offers improved control over density reduction while potentially maintaining acceptable compressive

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strength and overall mechanical performance. However, the combined effects of multiple mixture parameters on the performance of EPS adhesive–based lightweight concrete are highly interdependent and non-linear, making conventional one-factor-at-a-time experimental approaches inefficient and insufficient. In particular, variations in the W/C ratio, S/C ratio, and EPS volume fraction simultaneously influence density, pore structure, and mechanical performance. Therefore, a systematic and statistically robust optimisation approach is required to capture these interactions and identify an optimal mixture design. To this end, Response Surface Methodology (RSM) is employed as an efficient tool for mixture optimisation and proportioning under complex multi-parameter interactions [7-8]. Recognising the limited literature on optimising mixtures with EPS adhesive solutions, this study aims to: (i) evaluate the effects of W/C ratio, S/C ratio, and EPS volume fraction on compressive strength and density; (ii) develop predictive statistical models; and (iii) identify an optimal mixture design based on the RSM method. By addressing these objectives, the research seeks to fill a critical gap in the literature and provide practical guidance for designing lightweight concrete using EPS as a binder solution rather than conventional granules.

2. MATERIALS AND METHODS

2.1. Materials

The primary binder used was Ordinary Portland Cement (OPC) (ASTM C150 Type I, ρ = 3120 kg/m^3), combined with natural river sand (ρ= 2620 kg/m^3) as fine aggregate. Silica fume (SF) (ρ = 2200 kg/m^3) was included at a constant 10% by cement mass to enhance particle packing and microstructural densification. The lightweight component was a novel EPS solution, prepared by dissolving post-consumer EPS foam in RON 95 gasoline until a saturated transparentglue-like solution.Potable water was used for all mixtures.

2.2. Experimental Design and Variables

Response Surface Methodology (RSM) with a Central Composite Design (CCD)was adopted to investigate the effects of the mixture parameters on compressive strength and density. The independent variables were:A - (W/C); B - (S/C); C - EPS solution volume fraction (%EPS). Each factor was evaluated at three primary levels (low, center, high), expanded with axial points to enable model curvature. The coded and actual factor levels are provided in Table 1. The design consisted of 17 experimental runs, including factorial points, axial points, and replicated center points to allow estimation of pure error and assess model adequacy.

Table 1. Independent variables and levels used in CCD

Factor	Description	Low	Center	High
A	W/C ratio	0.35	0.45	0.55
B	S/C ratio	1.50	2.25	3.00
C	EPS volume (%)	10%	25%	40%

2.3. Mixing Procedure and Testing Procedures

Lightweight concrete preparation utilized a three-stage mixing sequence. First, cement, sand, and silica fume were dry-blended for 5 minutes. Second, water was added, and the mixture was blended for 3 minutes to form the cement paste. Finally, the EPS adhesive solution was gradually added, and mixing continued for 30 minutes to ensure micro-scale polymer dispersion and prevent segregation.

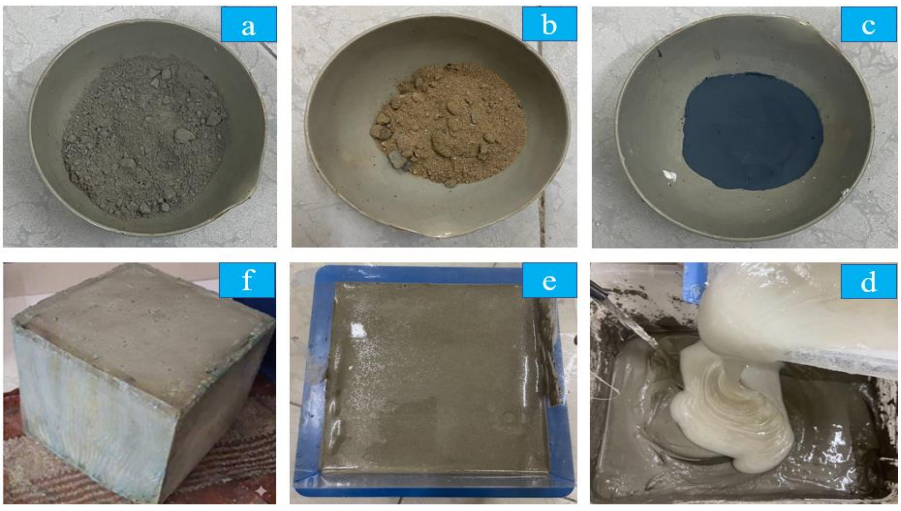

Figure 1. Fabrication of lightweight concrete: a- cement, b- sand, c- silica fume, d- mixing EPS solution into cement mortar, e- pouring concrete into the mold, f- concrete specimen after 28 days of curing

Mixtures were cast into 150 mm x 150 mm x 150 mm cubic moulds and then cured in a wet environment for 28 days before compressive strength and density testing (Fig. 1). Compressive strength was determined in accordance with EN 12390-3:2019 using a universal testing machine [9]. Density was calculated using the oven-dry mass (at 105 Cto constant weight) divided by the geometric volume [10].

2.4. Statistical Modeling and Optimization

The experimental data were fitted to a second-order polynomial model of the form:

$$Y=\beta_0+\sum\beta_i X_i+\sum\beta_{ii}X_i^2+\sum\beta_{ij}X_iX_j\ldots \quad (1)$$

Where Y represents compressive strength or density, X_i are the encoded variables (A, B, C), and β terms are regression coefficients.ANOVA was used to determine the significance of factors and interactions, evaluate model adequacy (R^2, adjusted R^2), and assess lack-of-fit. Response surface plots were generated to visualize factor effects. Multi-response optimization was carried out using the desirability function approach to identify a balanced mixture achieving high strength and low density.

3. RESULTS AND DISCUSSION

3.1. Model Diagnostics Based on Experimental and Predicted Values

Table 2 compares experimental and predicted compressive strength and density for all 17 (CCD) runs, alongside residuals. The close alignment between predicted and experimental values confirms the adequacy of the developed regression models in representing the influence ofW/C,S/C, and EPS content. Absolute residuals for compressive strength were ≤ ±0.30 Mpa (< 2% deviation), and density residuals were ≤ ± 7.7 kg/m^3 (<1% deviation). This strong agreement validates the accuracy of the fitted models and the suitability ofRSM [11-13]. A clear trend emerged regarding mixture variables: higher EPS content and increased W/C ratio predictably led to reductions in both compressive strength and density due to increased porosity. Conversely, lower W/C ratios and moderate S/C levels enhanced compressive strength. Run 16 achieved the maximum strength (18.2 MPa) at a density of 1288.8 kg/m^3. Mixtures with 40% EPS and higher W/C ratios (Run 12) resulted in the minimum strength (9.3 MPa) and lowest density (820.9 kg/m^3), illustrating the inherent performance/light weight trade-off.

Table 2. Comparison between experimental and predicted responses

Runs	Input variables			Compressive strength (Mpa)			Density (kg/m^3)		
	W/C	S/C	EPS (%)	Experimental value	Predicted value	Residual	Experimental value	Predicted value	Residual
1	0.45	2.25	25	17.1	16.95	0.1493	1253.2	1251.10	2.10
2	0.35	3	10	16.1	16.29	-0.1920	1190.1	1189.60	0.5045
3	0.55	3	10	15.6	15.56	0.0380	1188.2	1189.27	-1.07
4	0.45	2.25	10	16.8	16.62	0.1780	1257.4	1250.55	6.85
5	0.55	1.5	10	17.6	17.62	-0.0220	1431.5	1437.31	-5.81
6	0.55	3	40	9.4	9.44	-0.0420	835.1	835.03	0.0745
7	0.45	2.25	25	16.7	16.95	-0.2507	1248.2	1251.10	-2.90
8	0.35	3	40	11.3	11.32	-0.0220	1060.4	1055.01	5.39
9	0.45	2.25	25	16.7	16.95	-0.2507	1248.6	1251.10	-2.50
10	0.55	2.25	25	16.6	16.72	-0.1220	1203.4	1195.69	7.71
11	0.35	1.5	10	18.1	18.10	-0.0020	1415.2	1415.69	-0.4855
12	0.55	1.5	40	9.3	9.15	0.1480	820.9	821.82	-0.9155
13	0.45	2.25	40	9.9	9.90	-0.0020	870.3	875.51	-5.21
14	0.45	1.5	25	17.2	17.24	-0.0420	1374.1	1367.55	6.55
15	0.45	3	25	16.7	16.48	0.2180	1256.2	1261.11	-4.91
16	0.35	2.25	25	18.2	17.90	0.2980	1288.8	1294.87	-6.07
17	0.35	1.5	40	10.7	10.78	-0.0820	1020.5	1019.85	0.6545

3.2. Predicted and actual values: scatter plot evaluation

The models for compressive strength and density were validated using scatter plots (Fig. 2a and 2b). Data points in both plots cluster tightly along the 45° reference line, indicating a strong correlation between experimental and predicted outputs. This alignment confirms the models' high predictive accuracy and ability to successfully capture the variability introduced by the mixture parameters, with negligible deviation or systematic error, thereby reaffirming their reliability for lightweight concrete incorporating EPS solution.

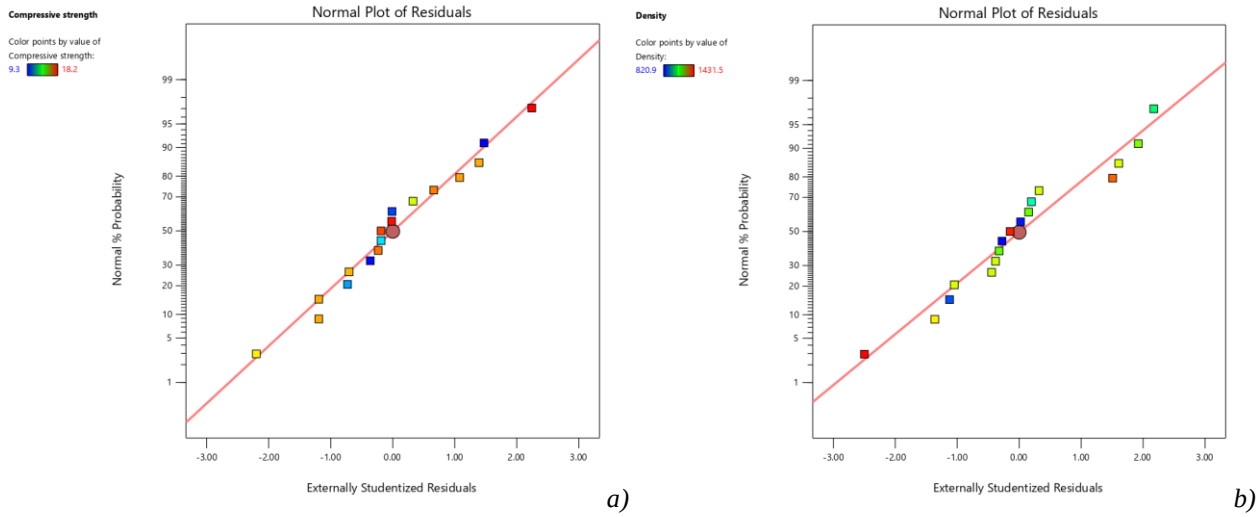

Figure 2. Comparison of predicted and experimental responses of lightweight EPS concrete: (a) compressive strength, and (b) density

3.3. ANOVA and significance of model terms

ANOVA analyses (Tables 3 and 4) confirm that the regression models for both compressive strength and density are statistically significant (p-value< 0.0001) [14]. The insignificant lack-of-fit tests further demonstrate model adequacy, accounting for important nonlinear trends[13,14]. For compressive strength (Tab. 3), W/C (A) and EPS content (C) were the most influential parameters.

Table 3. ANOVA for the Quadratic model of the compressive strength

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	173.48	9	19.28	335.34	< 0.0001	significant
A-W/C	3.48	1	3.48	60.56	0.0001	
B-S/C	1.44	1	1.44	25.12	0.0015	
C-EPS	112.90	1	112.90	1964.08	< 0.0001	
AB	0.0313	1	0.0313	0.5437	0.4849	
AC	0.6612	1	0.6612	11.50	0.0116	
BC	2.76	1	2.76	48.04	0.0002	
A^2	0.3497	1	0.3497	6.08	0.0431	
B^2	0.0211	1	0.0211	0.3670	0.5638	
C^2	36.46	1	36.46	634.23	< 0.0001	
Residual	0.4024	7	0.0575			
Lack of Fit	0.2957	5	0.0591	1.11	0.5370	not significant
Pure Error	0.1067	2	0.0533			
Cor Total	173.88	16				

Table 4. ANOVA for the Quadratic model of the density

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	5.780E+05	9	64221.60	1395.57	< 0.0001	significant
A-W/C	24591.68	1	24591.68	534.39	< 0.0001	
B-S/C	28323.68	1	28323.68	615.49	< 0.0001	
C-EPS	3.516E+05	1	3.516E+05	7641.25	< 0.0001	
AB	240.90	1	240.90	5.23	0.0560	
AC	24123.06	1	24123.06	524.21	< 0.0001	
BC	34125.78	1	34125.78	741.57	< 0.0001	
A^2	90.68	1	90.68	1.97	0.2032	
B^2	10712.52	1	10712.52	232.79	< 0.0001	
C^2	94763.36	1	94763.36	2059.25	< 0.0001	
Residual	322.13	7	46.02			
Lack of Fit	306.69	5	61.34	7.95	0.1156	not significant
Pure Error	15.44	2	7.72			
Cor Total	5.783E+05	16				

Highly significant quadratic terms (A^2 and C^2) indicated strong surface curvature, while the A x C interaction was meaningful, reflecting increased EPS sensitivity at higher W/C ratios [15]. For density (Tab. 4), EPS content (C) was the dominant factor, consistently causing density reduction. S/C (B) had a notable secondary influence. Significant quadratic terms again confirmed the nonlinear behaviour across the design space. High values of R^2, adjusted R^2, and predicted R^2, along with low PRESS values, further validated the reliability of the models for both responses. The regression equations from RSM are:

$$\textit{Compressive strength} = 22.55380 - 31.74742A - 0.727363B + 0.564468C + \\ +0.833333AB - 0.191667AC + 0.052222BC + 36.12676A^2 - 0.157746B^2 - 0.016394C^2 \quad (2)$$

$$\textit{Density} = 1715.95663 + 1107.51784A - 689.03304B + 32.70272C - 73.16667AB - \\ - 36.60833AC + 5.80556BC - 581.76056A^2 + 112.41315B^2 - 0.835856C^2 \quad (3)$$

Following the criterion that terms with p-values greater than 0.1000 can be excluded, yielding the reduced regression equations:

$$\textit{Compressive strength} = 22.55380 - 31.74742A - 0.727363B + 0.564468C - \\ - 0.191667AC + 0.052222BC + 36.12676A^2 - 0.016394C^2 \quad (4)$$

$$\textit{Density} = 1715.95663 + 1107.51784A - 689.03304B + 32.70272C - 36.60833AC + \\ + 5.80556BC + 112.41315B^2 - 0.835856C^2 \quad (5)$$

The reduced regression modelsidentify EPS content as the primary factor controlling compressive strength, with excessive EPS addition markedly reducing strength, while W/C and S/C act as secondary modifiers through nonlinear and interaction effects. Conversely, density is mainly governed by W/C and S/C, with EPS providing essential non-linear contributions. These results highlight the need for joint optimisation of all three parameters to achieve low-density lightweight concrete without compromising mechanical performance.

3.4. Response Surface Analysis

Figure 3 illustrates the combined effects of W/C, S/C, and EPS content on compressive strength. At the central EPS level, changes in W/C and S/C produce only mild variations in strength, showing that their individual influence is limited. In contrast, the W/C–EPS surface shows a clear strength reduction as EPS increases, especially at higher W/C, while the S/C–EPS surface indicates that the beneficial effect of sand content weakens when EPS becomes dominant. These trends confirm that EPS is the primary factor governing compressive strength, whereas W/C and S/C mainly contribute through interaction effects, consistent with the ANOVA results and the regression model [14,15].

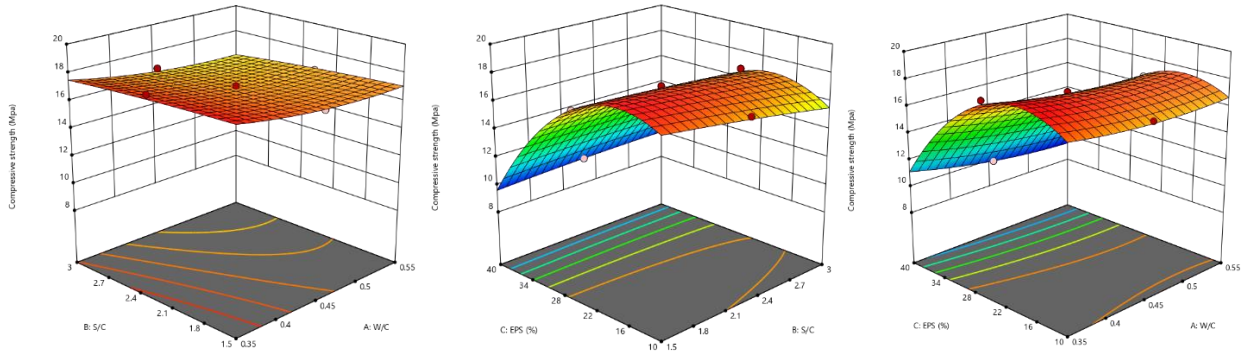

Figure 3. Response surface analysis of the effects of mixture parameters on compressive strength

The contour plots in Fig. 4 show that compressive strength increases with lower W/C and higher S/C ratios, reflecting better packing. Increasing EPS sharply reduces strength, especially at high W/C, due to weakened matrix cohesion [15-16]. Although higher sand content slightly offsets this effect, EPS remains the dominant factor reducing strength. Overall, the contours confirm that W/C and S/C influence strength through packing and water demand, while EPS consistently decreases performance, in agreement with ANOVA.

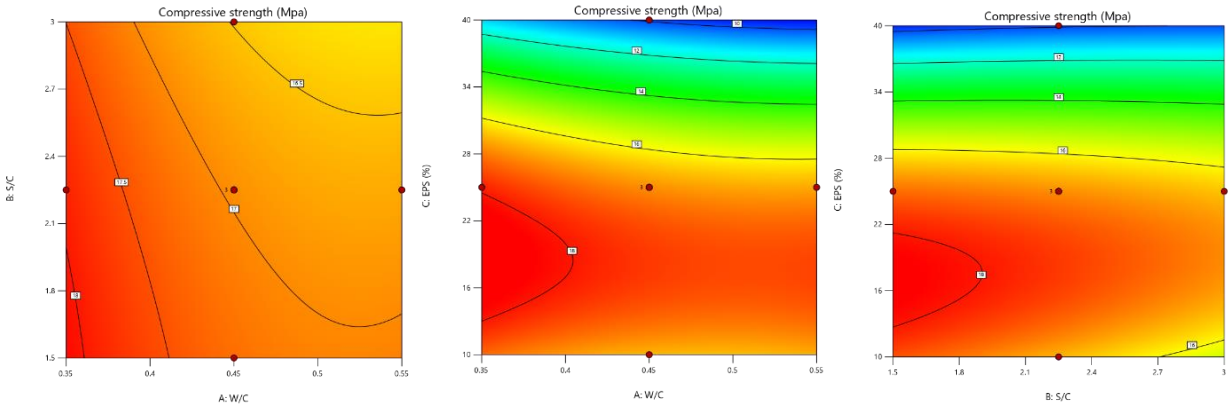

Figure 4. Contour plots of compressive strength as a function of W/C, S/C, and EPS contents

Figure 5 confirms that density is governed mainly by S/C and EPS, with EPS being the dominant factor controlling nonlinearity. The W/C–S/C surface is nearly flat, confirming minimal W/C–S/C interaction (consistent with ANOVA). Conversely, the W/C–EPS and S/C–EPS surfaces exhibit strong curvature, reflecting significant nonlinear interactions. Specifically, at higher EPS levels, the negative quadratic effect causes a sharp drop in density, and S/C also shows a nonlinear trend where density decreases sharply before stabilizing.

Figure 6 shows that density decreases sharply with increasing EPS, due to its much lower density than cement and sand. Higher cement content leads to denser mixtures, while W/C has only a minor effect, slightly reducing density through added porosity. Overall, EPS is the main factor controlling density. Compared with strength behaviour, an opposite trend appears: the density reduction from EPS also lowers compressive strength, highlighting the trade-off between lightweight characteristics and mechanical performance.

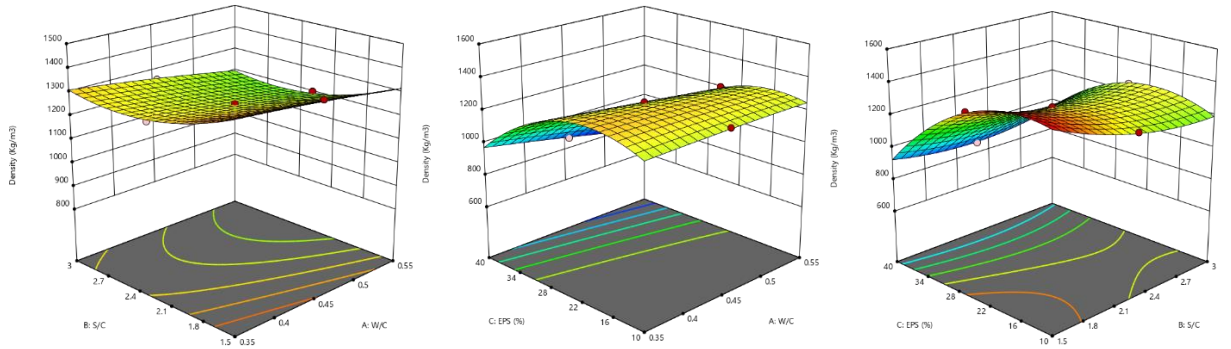

Figure 5. Response surface analysis of the effects of mixture parameters on density

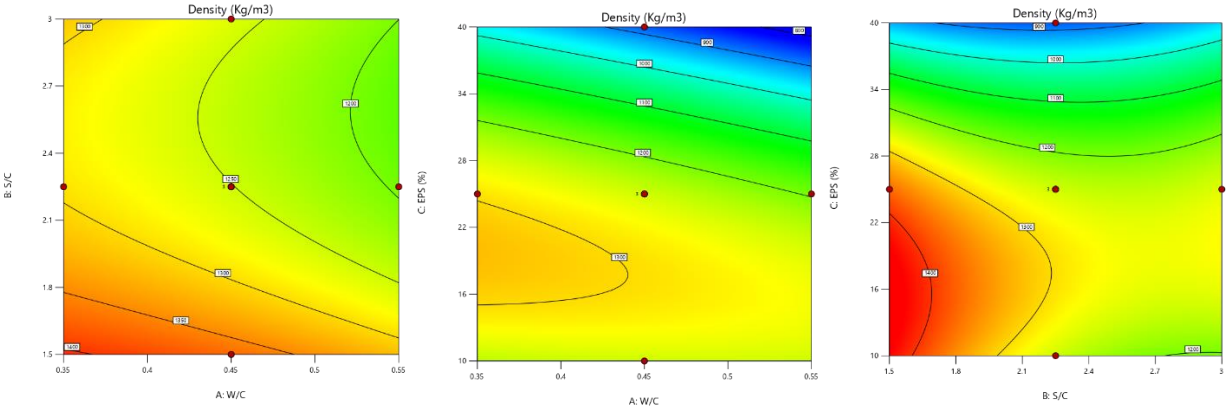

Figure 6. Contour plots of density as a function of W/C, S/C, and EPS contents

3.5. Multi-Response Optimization

3.5.1. Optimal Mixture Composition

Addressing the inherent trade-off where increased EPS adhesive solution simultaneously lowers compressive strength and density, a practical performance window was defined for optimization: 8-12 MPa for strength and 900-1000 kg/m^3 for density, suitable for non-load-bearing elements [17-18].To achieve a balanced mixture design, multi-response optimization using the desirability function was employed. This method converts the conflicting objectives of maximizing strength and minimizing density into individual and then combined global desirability indices (0-1), providing an efficient means to satisfy the defined targets simultaneously. Equal weighting was assigned to both responses. The optimisation yielded a global desirability of D = 1.000, indicating that the model successfully identified a mixture satisfying all performance targets. The optimal composition was W/C = 0.46, S/C = 1.76, and EPS = 38.65%, predicting compressive strength of 10.64 MPa compressive strength and density of 939.20 kg/m^3 (Fig. 7). This mixture achieves an effective balance between lightweight characteristics and mechanical performance, delivering an ultralight density (<1000 kg/m^3) while maintaining strength above the typical threshold for non-load-bearing lightweight concrete.

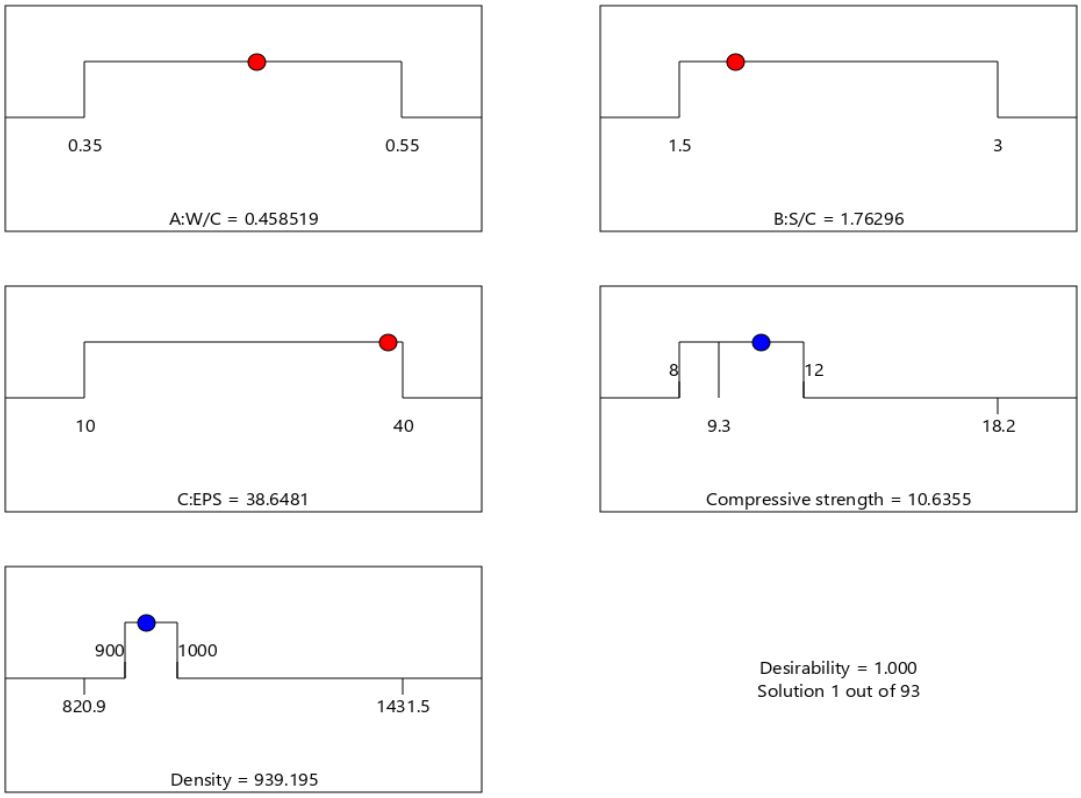

Figure 7. Response optimization of mix proportions for EPS-based lightweight concrete

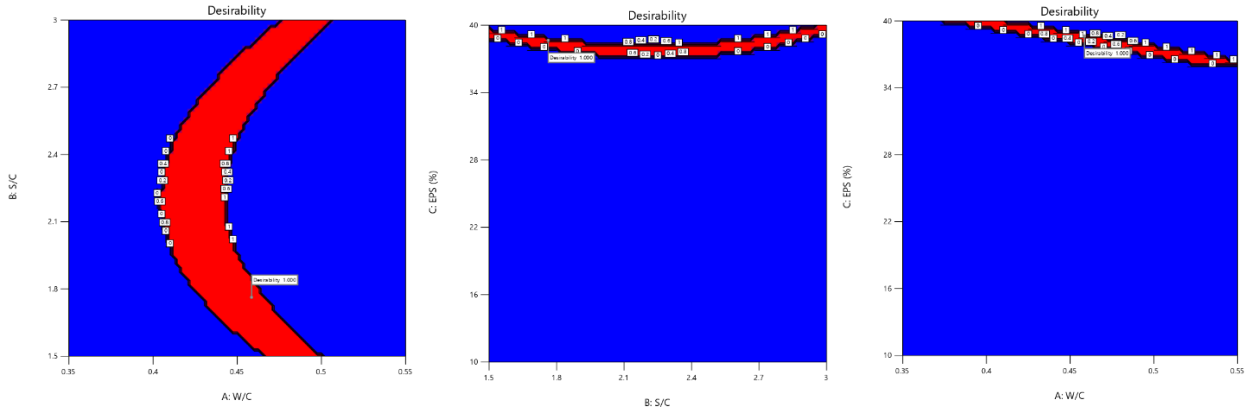

Figure 8. Contour plots of desirability for simultaneous optimisation of compressive strength and density in EPS-based lightweight concrete

The desirability contour plots (Fig. 8) define the optimal mixture zone (D=1.000) where both strength and density requirements are met. The W/C ratio and EPS content are the dominant factors. The W/C ratio is highly sensitive, with the optimal region narrowly confined to 0.40-0.46 (A-B plot), where small deviations drastically reduce desirability. Conversely, the S/C ratio shows broader acceptability (≈ 1.8-2.5). Both B-C and A-C plots emphasize that high EPS content (≈ 37-40%) is essential for achieving the low-density target while maintaining strength. In summary, optimal performance is critically dependent on precise W/C control combined with elevated EPS content, while S/C provides more flexibility.

3.5.2. Validation Experiment

To verify the accuracy of the predicted optimum, experimental validation was conducted using rounded mixture proportions (W/C = 0.50, S/C = 1.80, EPS = 39%). The experimentally obtained compressive strength (10.4 MPa) and density (935 kg/m³) showed excellent agreement with the model predictions, with deviations of less than 2.3% for strength and 0.5% for density. This strong agreement confirms not only the robustness of the developed response models, but also their practical reliability for guiding mixture design of EPS adhesive–based lightweight concrete. Building on this validated optimisation framework, the present study provides practical guidance for designing lightweight concrete using an EPS adhesive solution, which enables superior matrix integration and more uniform dispersion compared to conventional EPS beads, thereby improving material homogeneity and mechanical stability. The optimised mixture (ρ ≈ 939 kg/m³; compressive strength > 10 MPa) is suitable for non-load-bearing and semi-structural applications [16-18]. The RSM analysis further indicates that while increasing EPS content is effective in reducing density, careful control of the W/C ratio (≈ 0.46) is essential to preserve adequate strength. The strong predictive capability of the developed models supports their use in preliminary mixture design, reducing experimental trial efforts and enhancing overall efficiency. Overall, the proposed approach is practical, scalable, and conducive to sustainable lightweight concrete development.

4. CONCLUSIONS

This study examined the strength and density of lightweight concrete incorporating an EPS adhesive solution using RSM–CCD to assess and optimise the effects of W/C, S/C, and EPS content. Model diagnostics, including residual trends and predicted–actual correlations, confirmed strong agreement between experimental and predicted values, demonstrating the accuracy and reliability of the developed regression models. The response surface results showed clear nonlinear interactions: EPS content was the primary factor reducing density and compressive strength, while W/C strongly influenced mechanical performance. S/C contributed moderately to strength without significantly affecting density. Multi-response optimisation identified an optimal mixture withW/C of 0.46, S/C of 1.76 and EPS of 38.65%, yielding a predicted strength of 10.64 MPa and density of 939.20 kg/m³.Validation using rounded proportions produced closely matching results, confirming the robustness of the methodology. Overall, the findings demonstrate that the EPS adhesive solution offers a practical means of producing homogeneous, reliable lightweight concrete with substantially reduced density, supporting its broader application in civil engineering materials and lightweight structural components.

Conflict of interest

The authors declare no competing interests.

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IZVOD

PRIMENA METODE ODZIVNE POVRŠINE (RSM) U OPTIMIZACIJI GUSTINE I ČVRSTOĆE LAKOG BETONA KORIŠĆENJEM EPS RASTVORA

Ovaj rad se bavi izazovom balansiranja niske gustine i adekvatne čvrstoće kod lakog betona (LWC) predlažući novi pristup korišćenjem lepljivog rastvora od ekspandiranog polistirena (EPS) umesto konvencionalnih perli. Ovaj rastvor deluje i kao sredstvo za olakšavanje i kao pomoćno vezivo, efikasno prevazilazeći probleme poput uzgona, segregacije i slabog međupovršinskog vezivanja. Ugradnja rastvora nakon formiranja cementne paste obezbedila je jednoličnu disperziju i poboljšanu homogenost materijala. Metodologija odzivne površine (RSM) korišćena je za procenu interaktivnih efekata odnosa vode i cementa (W/C), peska i cementa (S/C) i zapreminskog udela EPS-a na čvrstoću na pritisak i gustinu. Optimizacija je dala maksimalnu poželjnost (D=1,000). Optimalna mešavina (W/C = 0,46, S/C = 1,76, EPS = 38,65%) predvidela je čvrstoću na pritisak od 10,64 MPa i gustinu od 939,2 kg/m^3. Eksperimentalna validacija pod zaobljenim uslovima (10,4 MPa i 935 kg/m^3) potvrdila je pouzdanost modela, demonstrirajući uspešan balans pogodan za primene koje ne zahtevaju opterećenje.

***Ključne reči**: Laki beton (LWC), EPS lepak, RSM, CCD, gustina, čvrstoća na pritisak, optimizacija mešavine.*

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