SSRG International Journal of Civil Engineering
ISSN: 2348-8352/ https://doi.org/10.14445/23488352/IJCE-V13I1P116

Volume 13 Issue 1, 187-197, January 2026

Original Article

Response Surface Methodology based Optimization of Low-Density Foamed Cement Mix Proportions

C. Raghu Rami Reddy[1], H. Sudarsana Rao[2], Vaishali.G.Ghorpade[3]

[1] *Department of Civil Engineering, Government Polytechnic, Andhra Pradesh, India.*
[1,2,3]*Department of Civil Engineering, JNTUA, Anantapur, Andhra Pradesh, India.*

[1]*Corresponding Author : phdworkraghu@gmail.com*

Received: 08 November 2025 Revised: 10 December 2025 Accepted: 09 January 2026 Published: 14 January 2026

Abstract - *This article provides an in-depth analysis of applying the Box-Behnken Design (BBD) approach in conjunction with Response Surface Methodology (RSM) to enhance the composition of Low-Density Foamed Cement (LDFC). This study investigated the mechanical characteristics of cement-based LDFC mixtures. Fly ash, silica fume, and metakaolin serve as Supplemental Cementitious Materials (SCMs) that replace portions of the cement, totalling up to 30% of the binder content. The dry density of LDFC mixes was evaluated between 400 and 800 kg/m³. Steel, glass, and polypropylene fibres are added in different amounts (from 0% to 2% by volume) to improve the ductility. The experimental investigation was performed to evaluate compressive and flexural strengths of LDFC mixes prepared with steel fibers, glass fibers, silica fume, fly ash, and Polycarboxylate Ether (PCE). LDFC with no fibers showed lower strength and brittle failure, reflecting its inherent weakness without reinforcement. By forming a fiber-cement network, steel fibres enhanced the flexural and compressive strengths. Pore volume decreased, and mechanical strength increased with a 15% addition of silica fume.*

Keywords - *Response Surface Methodology (RSM), Low-Density Foamed Cement (LDFC), Supplementary Cementitious Materials (SCM), Compressive strength, Flexural strength.*

1. Introduction

Foamed Concrete (FC), also known as cellular concrete, is a low-density material known for its self-compaction and the approximately uniform pore distribution. The low-density of concrete mixes is generally achieved by using different kinds of foaming agents. Achieved using different foaming agents [1] with a density between 300 and 1800 kg/m³. Due to practical challenges, the utilization of these mixes is limited to structural applications. FC-mixes are generally produced with lower cement contents and lower/no coarse aggregates; hence, these mixes produce less carbon footprint [2]. The main features of low-density foam mixes are i) excellent thermal insulation [3], ii) higher resistance to fire and sound insulation [4], iii) high porosity, and iv) higher weight-to-strength ratio [5]. These features enabled the increased utilization of foamed concrete mixes for both structural and non-structural applications [6], including lightweight fill for bridge abutments [7], airport buffer systems [8], precast components [9], and foundations [2, 10].

The incorporation of natural materials in concrete buildings negatively impacts both the environment and the economy [11]. In order to get around this, the researchers looked into using fly ash [13] and other supplemental cementitious materials in place of Portland cements, Rice Husk Ash (RHA) [14], blast furnace slag [15], silica-fume [16], and Waste Marble Powder (WMP) [33, 18]. Due to their higher silica content and finer texture [19], the extra cementitious materials improve mechanical and durability qualities [17]. Due to inexperience with concrete mixes, a substantial amount of waste is produced throughout the marble manufacturing process and is retained unused. This marble debris increases soil and air pollutants and lowers drainage system capacity. These problems can be eradicated or minimized by replacing the conventional materials with the marble waste in the concrete mixes [33]. Because marble waste is inert to cement hydration, it can be utilised in place of natural fine aggregates [17, 20]. Initial research by Binici [21] showed that substituting Waste Marble Powder (WMP) for limestone aggregates increased concrete's compressive strength by 76%. Similarly, Hebhpub [22] studied concretes with incremental replacement of limestone by WMP (0–100%), observing higher compressive strength but reduced workability. [23] investigated up to 40% replacement and reported decreases in density, compressive strength, and modulus of elasticity with higher WMP content, although freeze–thaw resistance improved. Martins [24] found that concretes with WMP as coarse aggregate could achieve comparable or superior flexural and compressive strengths relative to conventional concrete, but with higher water absorption. While Ural [26] found that a 5% substitution of WMP for fine aggregate produced the best strength and decreased porosity, Corinaldesi [25] noted increased compressive strength in self-compacting concrete with WMP addition. Additionally, Ulubeyli [27] emphasised that both conventional and self-compacting concretes containing WMP had improved durability qualities, such as decreased permeability and water absorption.

Compressive strength and corrosion resistance are further enhanced by its pozzolanic reactivity. While larger contents (10–12%) decreased performance and increased porosity, Hesami [28] showed that adding RHA (up to 8%) to fiber-reinforced pavement concrete improved compressive and tensile strengths. Due to its high silica content, RHA increased both fire resistance and compressive strength in geopolymer concretes, according to Nuaklong [30], whereas Gemma [29] showed better compressive and splitting tensile strengths for RHA concretes cured for 7–91 days. According to Bheel [34], replacing RHA (5%) with fly ash (5%) increased the material's compressive strength by 16.14% and its tensile strength by 15.20% when compared to the control. Hadipramana [31] evaluated FC with varying densities incorporating RHA, concluding that cement–sand–RHA foamed concretes exhibited higher compressive strength than control mixes at a 1:3:1 ratio.

Despite the versatility of foamed concrete in structural and non-structural applications, its utilization is often hindered by the inherent trade-off between ultra-low dry densities (400 to 800 kg/m³) and mechanical reliability. Fly ash and silica fume are examples of Supplemental Cementitious Materials (SCMs) that have been demonstrated to enhance performance and the environment in regular concrete; nevertheless, their behaviour in the high-porosity environment of foamed cement remains a challenging issue. Previous literature has explored individual components, such as the work by Hadipramana et al. on the optimization of foamed concrete with rice husk ash, or the studies by Hesami et al. regarding the inclusion of fibers in pavement applications. However, there is a significant research gap concerning the simultaneous, multi-variable interactive effects of high-volume SCMs (up to 30% binder replacement) and hybrid fiber networks (steel and glass fibers) within these low-density ranges. The adoption of a Box-Behnken Design (BBD) framework to methodically optimise these components is what makes this study novel, moving beyond the traditional 'one-variable-at-a-time' experimental approach. Unlike existing research findings that often focus on a single additive, this study explicitly defines the synergistic relationship between mineral admixtures and fibers that transforms the brittle failure of Low-Density Foamed Cement (LDFC) into a ductile, structurally competent material. By mapping these interactions through high-fidelity three-dimensional contour plots, this study establishes a refined mixed-design methodology that bridges the gap between material sustainability and structural performance.

By drastically lowering the amount of raw materials needed, the creation of Low-Density Foamed Cement (LDFC) naturally supports the sustainability of the building industry. The main strategy for reducing carbon footprints in this study is to replace up to 30% of Ordinary Portland Cement (OPC) with Supplementary Cementitious Materials (SCMs) such as fly ash and silica fume. The partial replacement of cement with industrial byproducts not only keeps waste out of landfills but also reduces global CO2 emissions and lowers the embodied energy of the final LDFC product. Furthermore, the ultra-low dry density range of 400–800 kg/m³ investigated here implies a substantial reduction in dead load for structural components, leading to secondary energy savings in transportation and the design of smaller, more efficient supporting structures.

The primary technical challenge in the development of Low-Density Foamed Cement (LDFC) is the inherent trade-off between achieving ultra-low dry densities, typically between 400 and 800 kg/m^3, and maintaining structural integrity, as these mixes often suffer from extreme brittleness and low strength. While the inclusion of Supplementary Cementitious Materials (SCMs) like fly ash and silica fume is known to densify the matrix, and fibers such as steel or glass are added to improve ductility and crack resistance, a significant research gap exists regarding the multi-variable interactive effects of these constituents. Most existing literature focuses on the impact of individual materials, leaving a void in understanding how a combined fiber-cement network and mineral admixtures simultaneously govern mechanical responses in foamed systems. By employing Response Surface Methodology (RSM) and Box-Behnken Design (BBD) to create empirical models that maximise the collaboration between these mix components and guarantee a balanced improvement of compressive and flexural performance, this work closes this gap.

Furthermore, this study advances the understanding of LDFC by establishing its structural reliability through a direct comparison with recent research findings. First, while Hadipramana et al. demonstrated the benefits of rice husk ash in foamed concrete, their work did not account for the high-volume synergistic effects of steel and glass fibers in the ultra-low density range. Second, Hesami et al. reported that high replacement levels of mineral admixtures could lead to performance decreases, whereas our results indicate that a 30% silica fume replacement significantly maximizes flexural strength when integrated into a reinforced fiber network. Finally, whereas Gencel et al. focused on thermal and microstructural properties, this research provides a comprehensive optimization of mechanical load-bearing capacity and ductility. By mapping these interactions through three-dimensional contour plots, this study offers a novel, high-fidelity tool for engineering foamed cement mixes that achieve both extreme lightweight properties and structural competence.

1.1. Response Surface Methodology- Background

Response Surface Methodology (RSM), a well-known statistical and mathematical technique, is used to examine, evaluate, and enhance experimental systems where multiple variables simultaneously affect the result. [2]. Developing empirical connections that reflect the interplay between mechanical responses and mix-related parameters is beneficial. RSM often entails setting up experimental tests in a methodical manner and creating regression models to optimize the mix proportions for the best results [31]. Determining the influencing factors and responses using an appropriate experimental design, such as a simplex lattice design, Box-Behnken design, or Central Composite Design (CCD)—and carrying out trials in compliance with that design are the primary components of RSM [32]. Regression model development may benefit from the collected data. Analysis of Variance (ANOVA) is used in the statistical analysis model validation process to confirm the model's applicability and accuracy. To optimise the circumstances, response surface plot contours or numerical analysis are employed. RSM is shown to be utilised.

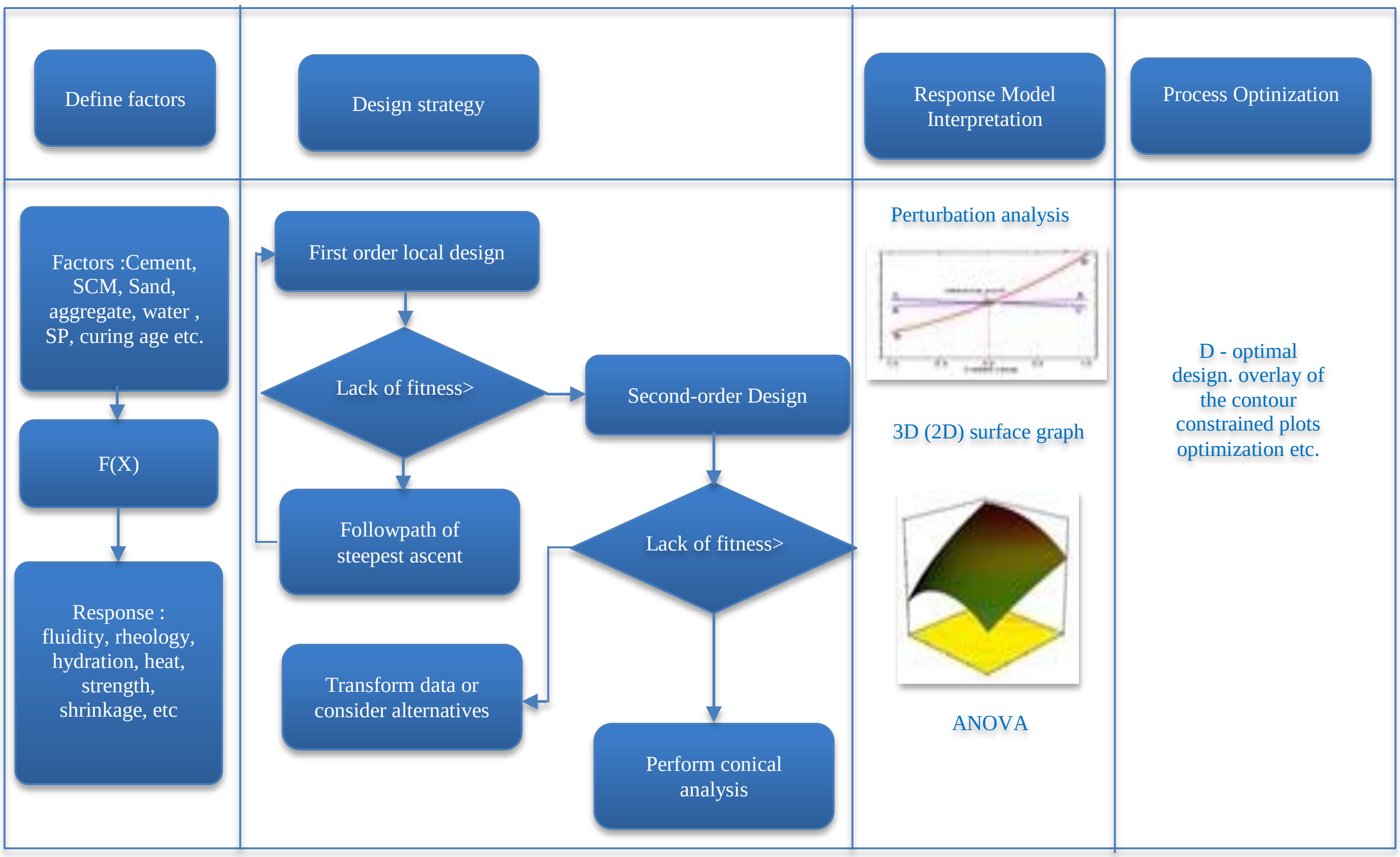


Fig. 1 RSM flow-chart for optimizing the experimental design (Li et al. 2022)

Widely used in the optimization of concrete mix and construction material components. A general approach for optimizing the mix constituents of concrete using RSM has been reported [2, 31, 32] and is illustrated in the following Figure 1.

The reliability of the experimental findings was rigorously verified through a comprehensive statistical validation process centered on ANOVA, which was utilized to confirm the significance and accuracy of the developed regression models. This analysis enabled the identification of the primary, quadratic, and interactive effects of variables, including fiber dosage, Supplementary Cementitious Material (SCM) content, and target density, on the resulting compressive and flexural strengths. The F-value and p-value were used to assess each model term; a p-value of less than 0.05 denoted a statistically significant impact on the mechanical response. The "Lack of Fit" test was conducted to ensure that the models accurately represented the experimental data within the specified design space.

In conducting this optimization, several critical statistical assumptions were made to maintain the integrity of the results: Initially, it was thought that a second-order polynomial equation could accurately represent the link between the independent variables and mechanical reactions.; second, it was assumed that experimental errors were independent and normally distributed with constant variance; and third, that the factor levels utilized in the Box-Behnken Design (BBD) were sufficient to capture the non-linear behavior of the Low-Density Foamed Cement (LDFC) mixes within the investigated density range of 400 to 800 kg/m³.

Response Surface Methodology (RSM) using a Box-Behnken Design (BBD) framework was necessary due to the complex, non-linear connections between fibre dosages and high-volume SCM replacements in a high-porosity foamed matrix. Unlike traditional experimental approaches, RSM allows for the simultaneous evaluation of multiple variables, providing a higher-fidelity understanding of the synergistic effects that govern the mechanical performance of LDFC.

BBD was specifically chosen over Central Composite Design (CCD) because it is more efficient for three-level factors and strategically avoids 'corner points', extreme combinations of variables that could lead to slurry segregation or foam instability in ultra-low-density ranges. This approach is supported by established literature, which highlights BBD's capability to generate accurate second-order polynomial models while minimizing the number of experimental runs. The reliability of these models was rigorously verified through Analysis of Variance (ANOVA), utilizing F-values and p-values to ensure that the identified primary and interactive effects were statistically significant ($p < 0.05$) and that the 'Lack of Fit' remained non-significant relative to pure error.

2. Materials and Methods

Fresh foamed concrete was cast right away into prism moulds measuring 160 × 40 × 40 mm for flexural strength testing and cube moulds measuring 70.6 mm for compressive strength testing. After being left for a full day, the specimens were demolded and cured in water at 27 ± 2 °C until the specified test ages. Flexural strength was evaluated using a three-point bending test, while compressive strength was evaluated using experimental testing carried out in accordance with IS:516 at 7, 14, and 28 days. The experimental data were evaluated using statistical models created as part of RSM in compliance with IS 4031 (part 8). [2, 31] A protein-based foaming agent was chosen for this study to produce a highly stable and fine-pored cellular structure.

The foam was generated using a high-pressure foam generator at a fixed dilution ratio, ensuring a consistent pre-formed foam density before being introduced into the cementitious slurry to achieve precise target dry densities ranging from 400 to 800 kg/m³. [2] Ordinary Portland Cement (OPC) and a ternary mixture of Supplemental Cementitious Materials (SCMs) such as fly ash, silica fume, and metakaolin were carefully blended to create the cementitious slurry. To improve the microstructural integrity of the Low-Density Foamed Cement (LDFC), these SCMs were used to replace up to 30% of the total binder content.

Fly Ash was added to improve particle packing and spherical lubrication within the mix, while Silica Fume was specifically chosen at 15% and 30% replacement levels to densify the matrix by reducing internal pore volume and strengthening the fiber-cement interface.

Furthermore, the inclusion of Metakaolin provided high reactive silica to accelerate early strength gain, ensuring that the ultra-low density skeleton (400–800 kg/m^3) remains structurally reliable and durable against brittle failure.

The stability of the foam during the blending process was critical to maintaining a uniform pore distribution, which directly influences the final mechanical properties of the mix. To improve the ductility and load-bearing capacity of the inherently brittle LDFC skeleton, three distinct fiber types—steel, glass, and polypropylene were incorporated at dosages ranging from 0% to 2% by volume. Steel fibers were selected for their high modulus to create a robust crack-bridging network and improve axial load-bearing capacity. Glass fibers were utilized to arrest micro-crack propagation and improve tensile resistance, while polypropylene fibers were included to control plastic shrinkage and enhance matrix toughness.

A Polycarboxylate Ether (PCE) superplasticizer was added to improve workability without altering the water-to-binder ratio [13, 31], and potable water satisfying IS: 456 requirements was used for both mixing and curing processes [35].

The effect of fiber inclusion, binder replacement, and target density on compressive and flexural strengths was studied, and optimization of mix components was done utilizing a Box-Behnken Design (BBD) and Response Surface Methodology (RSM) architecture [32, 2]. The primary and interacting impacts of the factors on strength attributes were captured in the experimental matrix. To obtain the necessary density, the pre-formed foam was mixed with a cementitious slurry made of binder, water, and superplasticizer.

The specimens were demolded and cured in water at 27 ± 2 °C until they achieved the test ages after being put for a full day. While flexural strength was determined using a three-point bending test, compressive strength was evaluated using experimental testing carried out in accordance with IS:516 at 7, 14, and 28 days, according to IS 4031 (part 8). The experimental results were analyzed through statistical models developed as part of RSM. The established statistical models were used for predicting the required mix proportions for obtaining a better mechanical response based on compressive and flexural strengths. The detailed discussion on response surface methodology is presented in the previous section [32, 2].

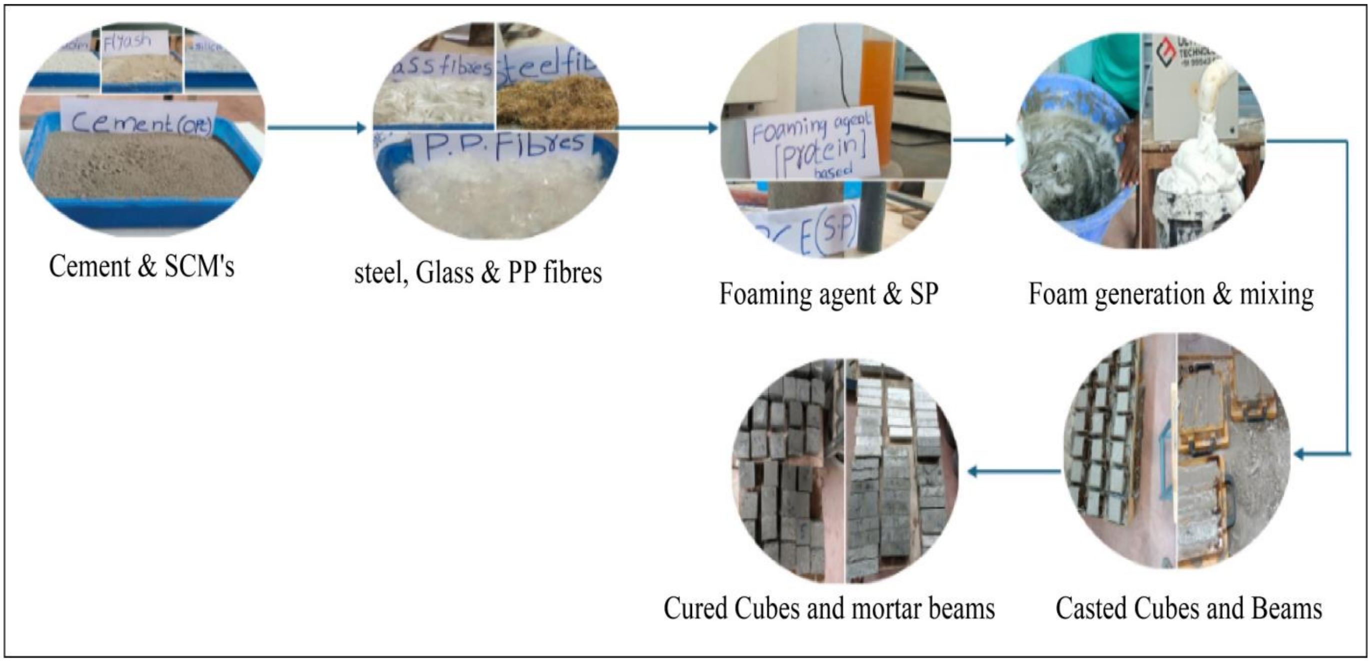


Fig. 2 Experimental workflow for the fibre reinforced foam cement mix

3. Results and Discussion

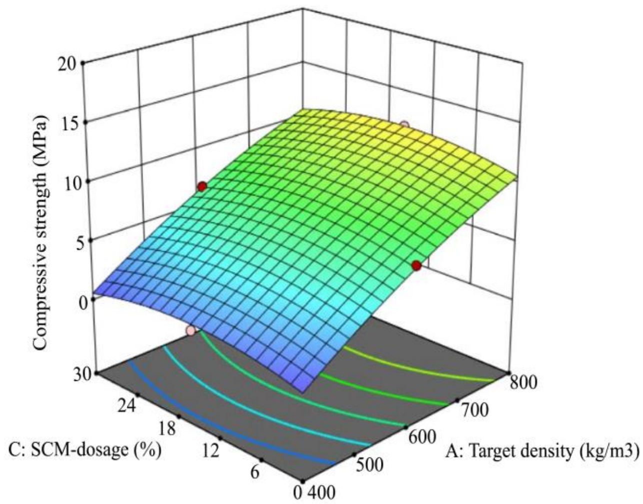
3.1. Compressive Strength

Compressive strength, the fundamental quality of concrete, characterises its capacity to bear axial forces without crushing. For both structural and non-structural applications, evaluating the compressive strength of Low-Density Foamed Concrete (LDFC) is essential.

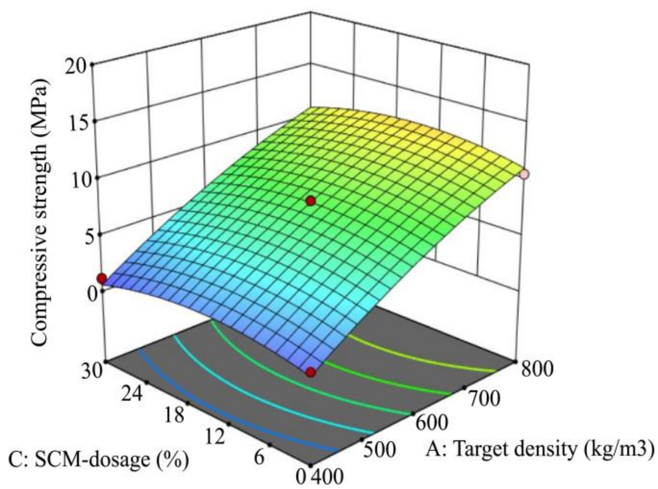
The compressive strength of cubic specimens was assessed in the current investigation with respect to the different mix components and their ratios. The kind and quantity of cementitious materials, fibre reinforcement, water-to-cement ratio, admixtures, curing conditions, and overall density were all changed in the current study. In the current investigation, SCMs like flyash or silica fume were utilised to improve foamed concrete's resistance to crushing. The LDFC mixes were created using fibres like steel, glass, and polypropylene, and the mechanical strength of LDFC mixes without fibres was compared with the equivalent results. The compressive strength of LDFC mixes was predicted using a regression model.

Table 1. Analysis of Compressive Strength trends based on target density and material synergy

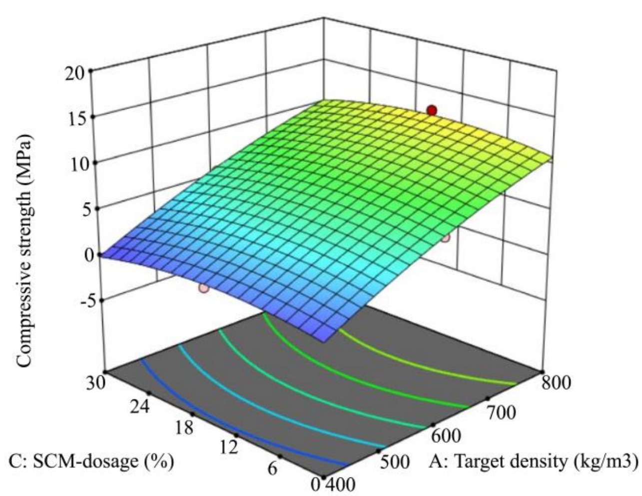
Mix Description	Target Density (kg/m³)	Fiber Volume (%)	SCM Type (30%)	Compressive Strength (MPa)	Technical Importance
Control LDFC	400	0%	Plain Binder	0.8 – 1.5	Represents the baseline porous skeleton; it exhibits inherent brittle failure.
Intermediate Mix	600	1%	Fly Ash	2.5 – 3.8	Increased density and matrix bridging via steel/glass fiber.
Optimized Mix	800	2%	Silica Fume	5.5 – 7.2	**Peak Performance:** Achieved through maximum densification and fiber-cement network.



(a) Fiber dosage of 0%



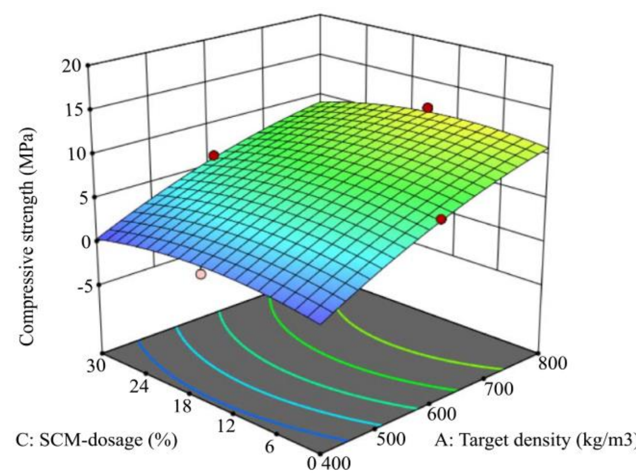
(b) Fiber dosage of 1%



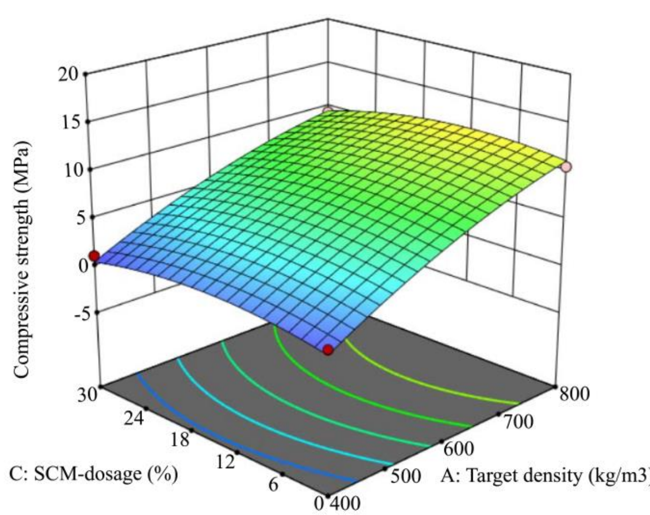
(c) Fiber dosage of 2%

Fig. 3 (a)-(c) Three-D contour plots for compressive strength of LDFC with steel fibers, flyash, and PCE from RSM.

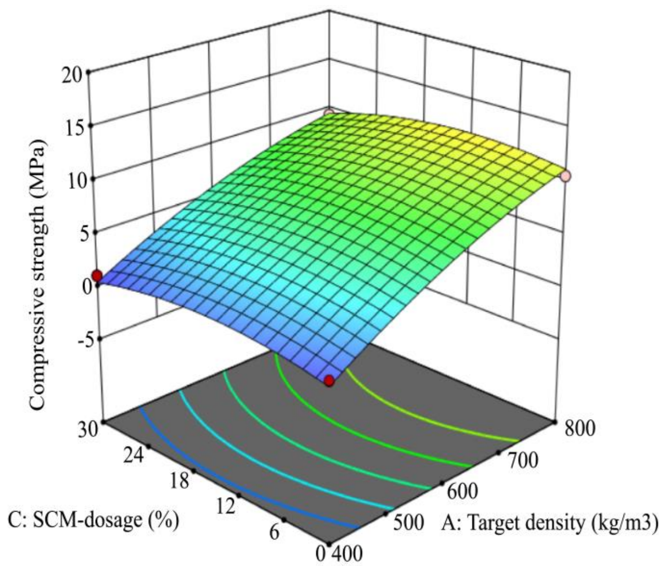
Figure 3(a) illustrates the contour plots for the compressive strength of Low-Density Foamed Concrete (LDFC) incorporating fly ash and PCE but without fibers. The plot shows generally low strength values, indicating the limited structural capacity of plain foamed concrete. Although fly ash and PCE contribute marginal improvements through matrix densification and better workability, the absence of fibers restricts mechanical enhancement. LDFC with 1% steel fibres is seen in Figure 3(b), where the compressive strength has increased noticeably. PCE guarantees adequate dispersion and flow, fly ash improves particle packing, and the fibres decrease crack propagation and increase load-bearing capacity. The contours amply demonstrate how fibres reinforce one another in a range of mixture proportions. At 2% steel fibre dosage, the compressive strength response is seen in Figure 3(c). Because a well-developed fibre network bridges cracks and arrests fractures, it offers notable strength increases. This combination, when combined with fly ash and PCE, produces the best strength performance, highlighting the complementary roles that fibres, SCMs, and admixtures play in improving the mechanical behavior of LDFC contour plots.



(a) Fiber dosage of 0%



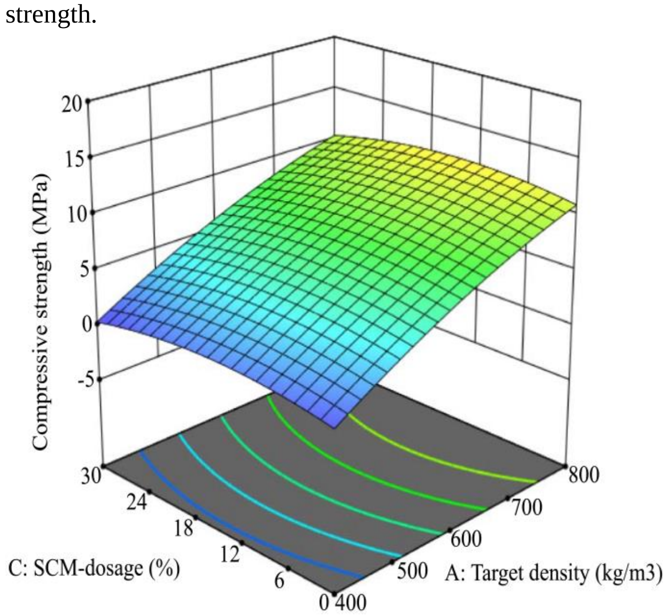
(b) Fiber dosage of 1%



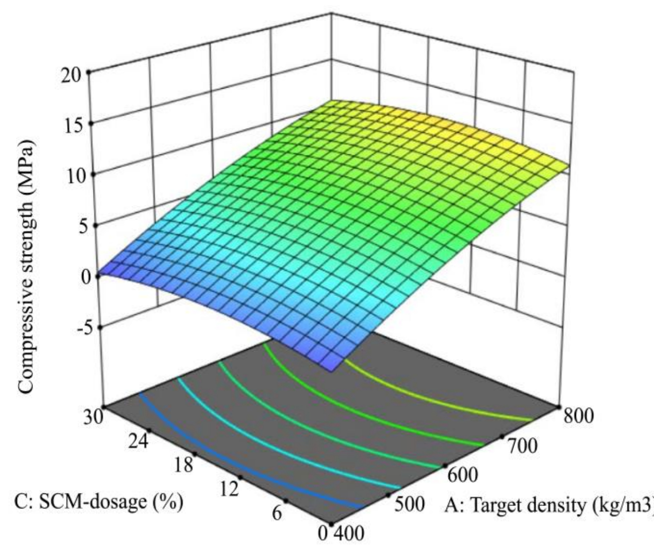
(c) Fiber dosage of 2%

Fig. 4 (a)-(c) Three-D contour plots for compressive strength of LDFC with glass fibers, flyash, and PCE from RSM.

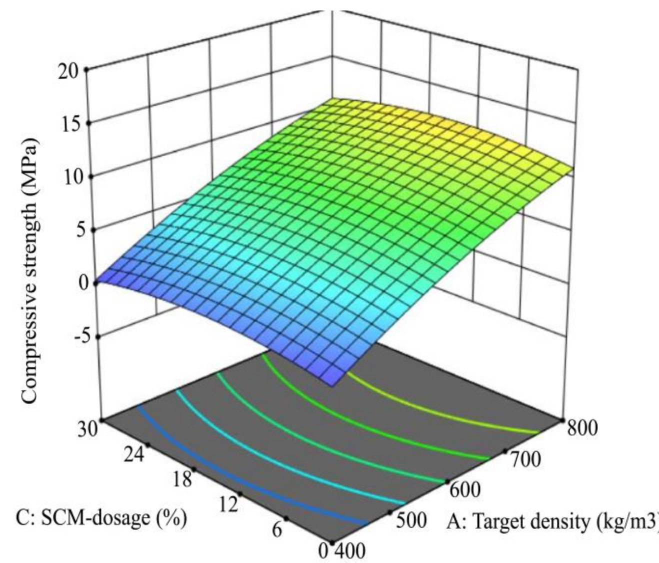
Figure 4 shows how SCM dosage and target density affect the compressive strength of LDFC with glass fibres at varying dosages (0, 1, and 2%). By decreasing brittleness, halting cracks, and more efficiently spreading stress, Figure 4(b) demonstrates that adding 1% glass fibres greatly increases the compressive strength of LDFC. Together, fly ash and PCE boost strength by improving matrix densification and ensuring appropriate fibre dispersion. A dense fibre network significantly increases fracture resistance, as shown in Figure 4(c), which also shows that 2% glass fibres offer the biggest strength benefits. Glass fibres, fly ash, and PCE work together to produce the best mechanical performance, amply demonstrating how increased fibre dosage maximizes strength.



(a) Fiber dosage of 0%



(b) Fiber dosage of 1%

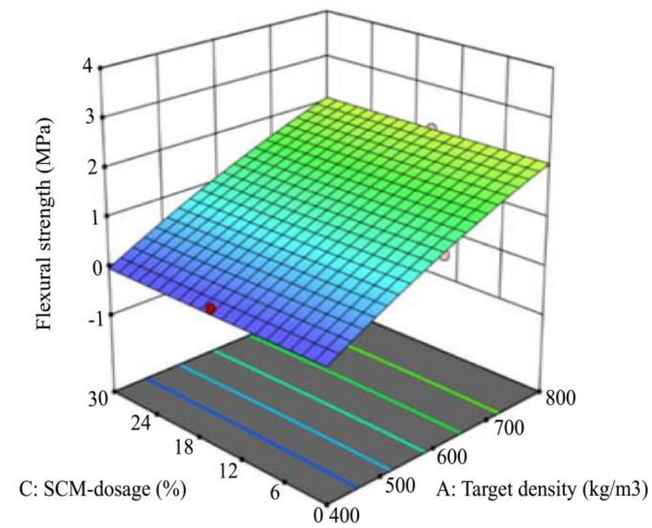


(c) Fiber dosage of 2%

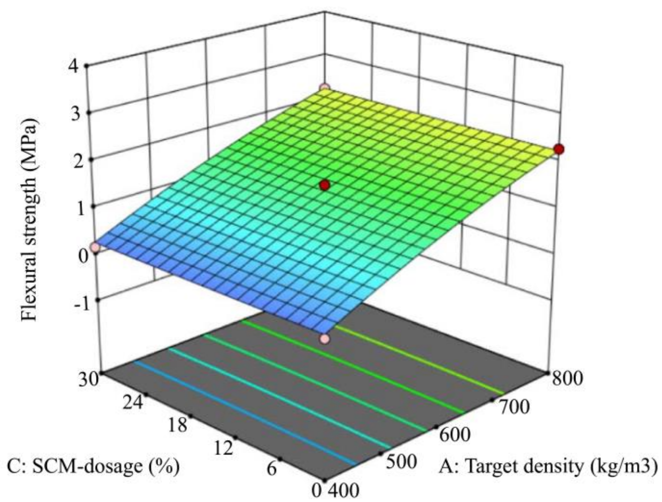
Fig. 5 (a)-(c) Three-D contour plots for compressive strength of LDFC with average over the other combinations.

3.2. Flexural Strength

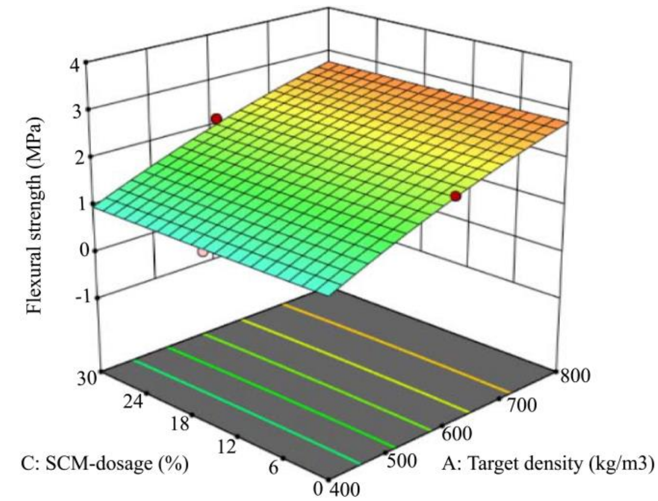
The flexural strength, also known as bending strength, represents the tensile resistance of the material under the action of bending. In the case of structural and semi-structural applications of Low-Density Foamed Concrete (LDFC) mixes, such as pavements, floor panels, and pre-cast members, the bending stresses are critical, and it is required to meet the minimum flexural strengths as per the desired application. The bending resistance of LDFC is significantly influenced by binder composition, target density, pore structure, and fiber inclusion. The enhanced ductility and bending resistance are contributed by the fiber presence. The presence of SCMs improves packing density, enhances interlocking at the fiber interface, and therefore increases flexural strength.



(a) Fiber dosage of 0%



(b) Fiber dosage of 1%



(c) Fiber dosage of 2%

Fig. 6 (a)-(c) Three-D contour plots for flexural strength of LDFC with steel fibers, flyash, and PCE from RSM.

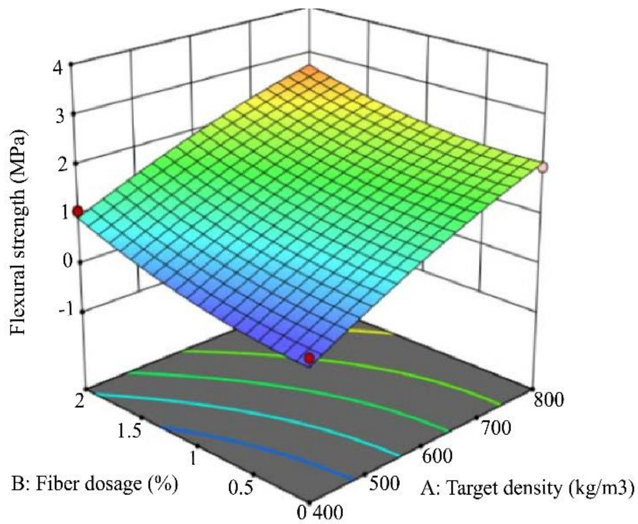
The contour plots in Figures 6 (a)-(c) present the changes in flexural strength of LDFC with different dosages of steel fibers. The LDFC mixes without the contour plots in Figures 6 (a)-(c) present the changes in flexural strength of LDFC with different dosages of steel fibers.

The LDFC mixes without fibers and with fly ash, and PCE resulted in lower flexural strength and brittle failure due to the absence of a better microstructure and interlocking. Whereas the addition of 1% fibers significantly increased the flexural strength and ductility due to better interlocking and bridging of cracks across the fibers, and the highest flexural strength and ductility were found for mixes with 2% steel fibers due to a robust reinforcement network. In summary, the contour plots demonstrated a strong synergistic effect of steel fibers, fly ash, and PCE in upgrading the flexural performance of LDFC.

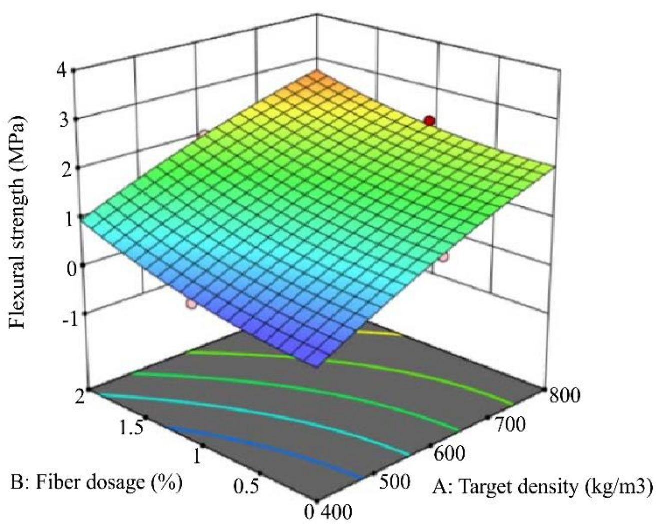
Table 2. Evaluation of Flexural Strength and ductility transitions in reinforced LDFC mixes

Mix Description	Fiber Type	Fiber Vol. (%)	SCM (%)	Flexural Strength (MPa)	Significance of Behavioral Shift
Non-Fibrous	None	0%	0%	0.2 – 0.4	Sudden catastrophic failure; lacks crack-bridging mechanisms
Standard Fiber	Glass/PP	1%	15%	0.8 – 1.2	Improved interlocking; fibers begin to arrest micro-crack propagation
High-Fibrous	Steel	2%	30%	2.2 – 3.5	**Optimal Ductility:** Robust reinforcement network maximizes energy absorption

The experimental data indicate a clear positive correlation between fiber volume and mechanical performance, with the most significant gains occurring at a 2% dosage. While LDFC without fibers fails prematurely due to its brittle skeleton, the 2% steel fiber network serves as a critical crack-bridging mechanism. However, this reinforcement is most effective when paired with 30% silica fume, suggesting that the optimal fiber-to-binder ratio is dependent on the matrix density. Beyond the 2% threshold, the challenge of maintaining uniform fiber dispersion in low-density slurries often leads to diminishing returns in strength-to-weight efficiency.



(a) Silica fume 15%



(b) Silica fume 30%

Fig. 7 (a)-(b) Three-D contour plots for flexural strength of LDFC with steel fibers and PCE from RSM.

Figures 7 (a)-(b) illustrate the contour plots of the response variable (flexural strength) of LDFC mixes with different dosages of steel fibers, different target densities, and silica-fume. The contour plots confirmed the positive influence of silica-fume inclusion on the flexural strength of LDFC mixes. At a replacement dosage of 15%, silica fume densified the LDFC skeleton by reducing the pore volume and led to a moderate increase in flexural strengths. In comparison, a higher dosage of 30% resulted in a significant increase in flexural strength due to better packing characteristics. The combined participation of fibers, silica-fume, and PCE admixture was more pronounced and resulted in better flexural response in terms of flexural strength and ductility.

4. Conclusion

This study presented the experimental investigation and response surface methodology for optimization of Low-Density Foamed Concrete (LDFC) through a systematic experimental program. Experimental evaluations of compressive and flexural strengths were conducted with four-point bending and axial compressive loads. To determine the individual and combined effects of steel fibres, glass fibres, fly ash, silica fume, and Polycarboxylate Ether (PCE) on mechanical behaviour, various combinations of these materials were assessed.

The impact of fibre dosage and Supplemental Cementitious Materials (SCMs) on strength development was clearly evident from three-dimensional contour plots produced using Response Surface Methodology (RSM). The studies included a variety of silica fume replacement levels (15% and 30%) and fibre dosages (0%, 1%, and 2%), with fly ash and PCE being uniformly added to all combinations. In order to minimise the carbon impact of lightweight infrastructure, practitioners densify the matrix and maximise compressive strength by substituting 30% of the cement binder with a ternary combination of fly ash and silica fume.

Third, construction professionals can utilize the developed 3D contour plots as a high-fidelity design tool to select precise mix proportions for applications such as bridge abutment fills, airport buffer systems, and precast wall panels. Finally, the use of Polycarboxylate Ether (PCE) is essential in field operations to ensure the uniform dispersion of fibers, ensuring that the optimized mechanical properties are consistent throughout large-scale structural pours. These findings were taken from the current investigation are,

- Low-density foamed cement mixes without fibers exhibited low compressive and flexural strength, confirming their brittle behavior.
- Steel fibers significantly enhanced flexural and compressive strength, with higher dosages forming an effective crack-bridging network.
- Silica fume replacement at 15% and 30% densified the matrix and resulted in an increased compressive strength.
- By combining fibres, fly ash, silica fume, and PCE, the most balanced improvement was produced, creating LDFC, a lightweight concrete that is structurally sound.

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