

Optimization of mechanical and thermal properties of hybrid lightweight aggregate foam concrete using central composite design

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Article Info	Abstract
Article History: Received 20 Jul 2026 Accepted 02 Sep 2026 Keywords: Foam concrete; Hybrid lightweight aggregates; Mechanical strength; Thermal properties; Response Surface Methodology (RSM); Central Composite Design (CCD)	This study addresses the development and improvement of foam concrete using a hybrid lightweight aggregate that includes natural lightweight aggregate (locally called Ponza), expanded clay (Leca), and expanded polystyrene (EPS), aiming to achieve a balance between mechanical properties and thermal performance while maintaining low density. The RSM and CCD were adopted to analyze the effect of different aggregate ratios and to develop predictive models. The results showed that the density ranged between 990–1295 kg/m³, compressive strength between 5.80–16.40 MPa, flexural strength between 1.27–3.81 MPa, and thermal conductivity between 0.382–0.595W/m·K. The statistical models showed acceptable agreement with the experimental results, with R² values ranging from 73.95% to approximately 88%. The thermal conductivity model exhibited the lowest R² value (73.95%), indicating relatively lower predictive accuracy compared with the other models. The results also indicated that Ponza is the most effective in improving mechanical properties. Leca contributed to reducing density and thermal conductivity. In contrast, expanded polystyrene led to improved thermal insulation at the expense of strength. The optimization process showed that the optimal mix consists of (17.85%) Ponza and (4.22%) Leca with no use of expanded polystyrene, achieving an optimal balance between strength, density, and thermal insulation. The study confirms the efficiency of using hybrid lightweight aggregates with the RSM to produce foam LWA concrete mixes with density range of (990–1295 kg/m³) and compressive strength from 5.80 to 16.40 MPa which, according to ACI 213R-14, are suitable for semi-structural engineering applications.

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1. Introduction

In recent years, lightweight concrete (LWC) has seen increasing interest due to its ability to reduce the dead loads of structures, improve thermal insulation properties and sustainability performance [1]. LWC generally has a practical density ranging from approximately 300 to 1850 kg/m³. According to ACI 213R-14, lightweight concrete is classified based on density and application into three main categories: low-density concrete (300–800 kg/m³) used for thermal insulation and non-structural purposes; structural lightweight concrete with a density of about 1350–1900 kg/m³ and a minimum compressive strength of 17 MPa; and moderate-strength lightweight concrete, which falls between these two categories with compressive strength ranging from 7 to 17 MPa [2]. LWC is concrete that can be achieved by replacing some of the solid materials with air voids and is divided into three types: the first is in the aggregate particles (lightweight aggregate concrete), the second is in the cement paste (foam concrete) and finally between the coarse aggregate particles by removing the fine aggregate (no-fine concrete) also known as No-fines concrete [3].

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Lightweight Aggregate Concrete is defined as a structural concrete in which traditional coarse aggregates are replaced with light-weight aggregates, commonly expanded clay, pumice as a way to reduce the overall density of the concrete without compromising its mechanical performance [4]. Foam concrete is a type of lightweight concrete produced by incorporating pre-formed foam into the cement paste to create evenly distributed air voids, significantly reducing its density. It is characterized by its light weight, high workability, and thermal insulation properties [5]. Despite the advantages offered by foam concrete [6], it suffers from a decrease in mechanical properties due to the increased void content within it. This limits its use in construction applications [7], necessitating the development of improved mixes that balance lightness and mechanical strength. Several researchers attempted to improve the properties of foam concrete.

Abbas and Hilal [8] investigated the use of waste plastic as partial replacement of fine and coarse aggregates in foam concrete. Different replacement ratios were used with 70% coarse plastic, it was observed that the amount of decrease in strength was about 9%, density decreased by 16%. When compared with the mix containing about 89% of fine and coarse plastic, the decrease in strength was about 24%, while the density decreased by 23%, indicating the possibility of using recycled plastic materials in the production of lightweight foamed concrete with improved mechanical properties and thermal insulation. Oday Asaad Abd et al. [9] studied the effect of using waste car tires with polypropylene fibers (separately and together) in foam concrete. The results showed a significant improvement in compressive strength, impact resistance, and damping properties compared to conventional foamed concrete, indicating the possibility of enhancing the mechanical performance of foam concrete using recycled materials reinforced with fibers. Another study [10] investigated the enhancement of foam concrete using various types of fibers including steel fibers, carbon fibers, glass fibers, and polypropylene with various lengths. Statistical enhancement techniques (RSM and CCD) were also adopted to determine the optimal ratios, resulting in improved compressive and tensile strength as well as impact properties.

Studies [11–13] have shown that the use of lightweight aggregates such as perlite, volcanic stone, and lightweight expanded clay aggregate (Leca) in the production of lightweight concrete effectively contributes to reducing density and thermal conductivity due to their porous nature. Controlling the proportions of these materials also allows for an appropriate balance between thermal insulation and structural requirements, making this type of concrete a suitable option for enhancing energy efficiency in buildings. One relatively recent technique is the use of expanded polystyrene (EPS) as an aggregate replacement in concrete. Early studies in this field date back to Cook (1972) [14], who used cork granules as a lightweight aggregate to produce low-density concrete. Since then, this field has developed significantly, with cork being adopted as a partial or complete replacement for aggregate to improve thermal properties and reduce the bulk density of concrete [15]. The use of cementitious additives such as fly ash and silica fume has proven effective in improving concrete properties [16]. Fly ash (FA), a byproduct of coal combustion in power plants, possesses pozzolanic properties that allow it to react with calcium hydroxide produced during cement hydration to form additional cementitious compounds (C-S-H). This leads to improved long-term strength, reduced permeability, and increased durability of the concrete [17–18]. Silica fume (SF), a byproduct of silicon or ferroalloy production, is characterized by its very fine particle size and high surface area. This helps fill microscopic voids, improve the internal density of the cementitious matrix and the interfacial zone, and thus significantly increase compressive strength [17].

In addition to improving mechanical properties, the use of fly ash and silica fume is a sustainable and environmentally friendly option, as they are industrial byproducts. This contributes to reducing industrial waste and cement consumption, thereby lowering carbon dioxide emissions associated with cement production [16]. Moreover superplasticizer (SP) was used to improve workability without increasing the water content. It allows for a reduction in the water-to-cement ratio while maintaining workability, leading to improved mechanical properties and reduced porosity. Combining these materials is an effective method for producing lightweight concrete with enhanced mechanical and thermal performance [17]. Although many studies have investigated the use of a single type of lightweight aggregate in concrete [11], relatively fewer studies have focused on incorporating lightweight aggregates into foamed concrete. Specifically, studies looking at the

simultaneous use of several types of lightweight aggregates in foamed concrete are still limited [19]. At the same time, many studies have used the RSM to optimize foamed concrete mixes. For example, Kurşuncu et al. [20] employed response surface methodology is employed to investigate the influence of waste marble powder, rice husk ash and foam content on compressive strength, flexural strength, porosity and thermal conductivity of foamed concrete. Other authors used the Box-Behnken design and response surface methodology to optimize the cement, water and foam contents to achieve the desired density and compressive strength [21]. Recently, RSM has also been used in multi-objective optimization of foamed cement concrete, by achieving a balance between compressive strength and thermal conductivity [22].

More recent studies have continued to develop this approach: Wang et al. [54] applied RSM to optimize the mix proportions of coal gangue-based geopolymers foamed concrete, while Mohamed et al. [55] combined RSM with an artificial neural network to optimize seashell-ash foamed concrete, both confirming the continued relevance of RSM-based optimization for foamed concrete mix design. Many studies have investigated the addition of lightweight aggregates to concrete, but fewer studies have focused on mixing lightweight aggregates with foam. Finding the optimal proportions of lightweight aggregates within this concrete is still in the process of research. Therefore, this research aims to develop a lightweight foamed concrete incorporating lightweight aggregates (individually or in combination) from different sources: natural lightweight aggregate (Ponza), Leca and EPS. The RSM is employed using Minitab program to determine the optimal proportions of these aggregates and evaluate their effects on responses of density, compressive strength, flexural strength, and thermal conductivity. Accordingly, the main objectives of this study are to: (1) investigate the effects of the proportions of Ponza, Leca, and EPS on the selected responses; (2) develop and validate RSM-based predictive models for the investigated responses; and (3) determine the optimum mix proportions that minimize density and thermal conductivity while maximizing compressive and flexural strengths. The expected engineering contribution of this study is to provide an optimized lightweight foamed concrete mixture incorporating natural, artificial, and recycled lightweight aggregates, offering a balanced combination of mechanical and thermal performance for potential engineering applications.

2. Response Surface Methodology (RSM)

RSM represents a robust mathematical and statistical technique used within the framework of Design of Experiments (DOE). Its development began mainly in the 1930s [23], with subsequent contributions from Box and his colleagues in the 1950s in developing response surface models [23]. The idea of RSM is based on studying the relationship between independent variables (input variables) and the resulting responses through a systematic experimental design to obtain an optimal response. This is achieved by finding empirical relationship between the inputs of any system, such as X, and the resulting response, such as Y [24], aiming to reduce the number of experiments while achieving the highest possible accuracy in the analysis. This methodology relies on constructing empirical mathematical models, often of the second order, which allow the description of the effects of individual variables as well as their interactions on the response. Thus, RSM provides an effective framework for understanding the behavior of a mathematical system and predicting outcomes without the need for a large number of laboratory tests [25].

RSM is considered one of the advanced statistical techniques that has been widely used in concrete technology. It is particularly useful for improving mix design and concrete properties in both fresh and hardened states. This application is important because concrete contains multiple components with overlapping effects [10][26]. Among the designs of the RSM, CCD is considered one of the most common and widely used designs, due to its ability to build accurate quadratic models, represent curvature in the response behavior, in addition to its efficiency in reducing the number of experiments required compared to conventional designs [27].

DOE is an approach that includes several experimental design methods, such as Response Surface Design (RSD), Central Composite Design (CCD), Box-Behnken Design (BBD), Doehlert Matrix (DM), three-level full factorial designs, and others are among the methodologies used [27]. In this study, the RSM methodology was adopted using a CCD design to analyze and optimize the effect of key variables in foam concrete [10] incorporating lightweight aggregate from different sources and

with different densities. Mathematical models were developed to link the mix inputs (input variables) including coarse aggregate (Ponza, Leca, EPS) with resulting properties (responses) such as density, compressive strength, flexural strength and thermal conductivity. These models were also used within an optimization process to determine the optimal mix that achieves the best balance between mechanical performance and physical properties while minimizing the number of laboratory experiments to the lowest possible level.

3. Experimental Details

3.1 Materials

To produce all foam concrete mixes, Ordinary Portland Cement (OPC) (Type I) was used with a specific gravity of 3.15 which conforms ASTM C150 [28]. Silica sand was used as a filler (fine aggregate) with particle size ranged between 0.6 and 1.18 mm. It was verified to be free from salts ensuring its suitability for concrete mixtures without adverse effects on concrete mechanical properties or durability with a specific gravity of 2.6. Fly ash (FA) used was Class F which conforms to ASTM C 618 [29]. Its specific gravity was 2.1 and it was added at a rate of 20% of the weight of silica sand. In addition, silica fume (SF) with a specific gravity of 2.2 conforms to ASTM C1240 [30], was added at a rate of 10% of the weight of cement [31]. Chemical compositions for cementitious materials used are presented in Table1.

To improve the workability and strength, superplasticizer (SP) (sika viscorete180 GS) was used in this study in a dosage of 1.5% of cement weight with specific gravity of 1.1 [31]. Foam was generated by mixing foaming agent 25gr for 1000g water with a density of 30 kg/m³, see Figure 1. In addition, tap water was used for mixing the concrete. Three types of lightweight aggregates (LWA) were adopted, see Figure 2. Firstly, natural lightweight aggregate (Ponza), which is porous volcanic material characterized by low density and an open pore structure. Secondly, artificial lightweight aggregate (lightweight expanded clay aggregate, Leca), produced through the thermal treatment of clay at high temperatures, resulting in an expanded material with a predominantly closed porous structure. Thirdly, expanded polystyrene (EPS), a synthetic lightweight aggregate characterized by extremely low density, closed-cell structure, and excellent thermal insulation properties. All aggregates were particles size distribution ranging from 4.75 mm to 10 mm conforms to ASTM C330/C330M-23 for lightweight aggregates used in structural concrete [32].

Table 1. Oxide compositions of cementitious materials (wt.%)

	SiO_2	CaO	Al_2O_3	Fe_2O_3	MgO	SO_3	K_2O_4
<i>Cement</i>	19.36	61.21	4.78	5.24	4.31	2.41	-
<i>Fly ash</i>	46.93	9.78	29.66	6.32	1.62	0.38	1.59
<i>Silica fume</i>	92.1	0.98	1.02	1.93	0.79	0.1	-



Fig. 1. Foam generator and produced foam



Fig. 2. Types of lightweight aggregates used

3.2 Mix Design

To achieve the lowest possible density using a selected type of lightweight aggregate, a water-displacement method was adopted. A 10×10×10 cm cube was filled with the selected LWA and the weight of the aggregate occupying the cube volume was measured as approximately 57% of the cube volume. The remaining volume (43%) was occupied by the mortar matrix. The quantities of all constituent materials were calculated using the absolute volume method [33], considering the specific gravity and required volume of each constituent to obtain the desired concrete mix proportions according to equation (1).

$$Absolute\ volume(m^3) = \frac{Weight(kg)}{Specific\ gravity \times Weight\ of\ water(1000kg/m^3)} \quad (1)$$

The value of 57% was the maximum total volume of LWA, so when used three types of lightweight aggregates, the range of each type was between (0-19) % by volume. This range represented the selected design ratios used as inputs in Minitab software to obtain the experimental mixes, as shown in Figure 5. Then, the volume of required foam can be measured to fill the remaining of the 1 m³. When the proportions of three types of aggregates set to zero, the foam represents 57% of volume, and this mixture is designated as the reference mix. The values of the cement used were 350 kg/m³, while the silica sand 388 kg/m³ and the amount of added fly ash 20% of silica sand weight when the amount of silica fume added 10% of cement weight. Water amount was 122.5 kg/m³ and superplasticizer 1.5% of cement weight mix proportions are presented in Table 2.

3.3 Production

Saturated surface-dry (SSD) condition adopted in this study for each Leca and Ponza. The aggregates were immersed in water for 24 h. After that, they were removed from the water, and the excess water on their surfaces was removed before mixing. To produce LWC, dry materials (cement, silica sand, silica fume, fly ash) were mixed firstly and then Ponza and Leca were added and mixed with the dry materials. After that, wet mixing was done after adding the mixing water approximately 80% of the total mixing water was added gradually while mixing continued [34]. The remaining 20% of the mixing water was premixed with the superplasticizer and then added to the concrete mixture. After that, prepared foam with a specified volume was added and mixed. For EPS mix, EPS was added after the foam to achieve uniform a mixture and to avoid the upward flotation of EPS. The fresh mixture was then cast in oiled plastic molds and covered with nylon sheets to prevent evaporation of water during the concrete hardening stage [19]. Figure 3 presents the flowchart of the manufacturing production process.

Table 2. Mix proportions of some selected mixes

Material	Mix1	Mix4	Mix5	Mix9	Mix10	Mix12	Mix13	Mix16	Mix20
Cement (kg/m ³)	350	350	350	350	350	350	350	350	350
Silica sand (kg/m ³)	388	388	388	388	388	388	388	388	388
Foam (L/m ³) (Density = 30 kg/m ³)	285	190	380	570	380	0	380	380	190
Ponza (kg/m ³) (Density = 795 kg/m ³)	75.5	75.5	151	0	0	151	0	0	151
Leca (kg/m ³) (Density = 590 kg/m ³)	56.05	56.05	0	0	56.05	112.1	112.1	0	56.05
EPS (kg/m ³) (Density = 12 kg/m ³)	1.14	2.28	0	0	1.14	2.28	0	2.28	1.14
Silica fume (kg/m ³)	35	35	35	35	35	35	35	35	35
Fly ash (kg/m ³)	77.6	77.6	77.6	77.6	77.6	77.6	77.6	77.6	77.6
W/C ratio	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Superplasticizer (kg/m ³)	5.25	5.25	5.25	5.25	5.25	5.25	5.25	5.25	5.25

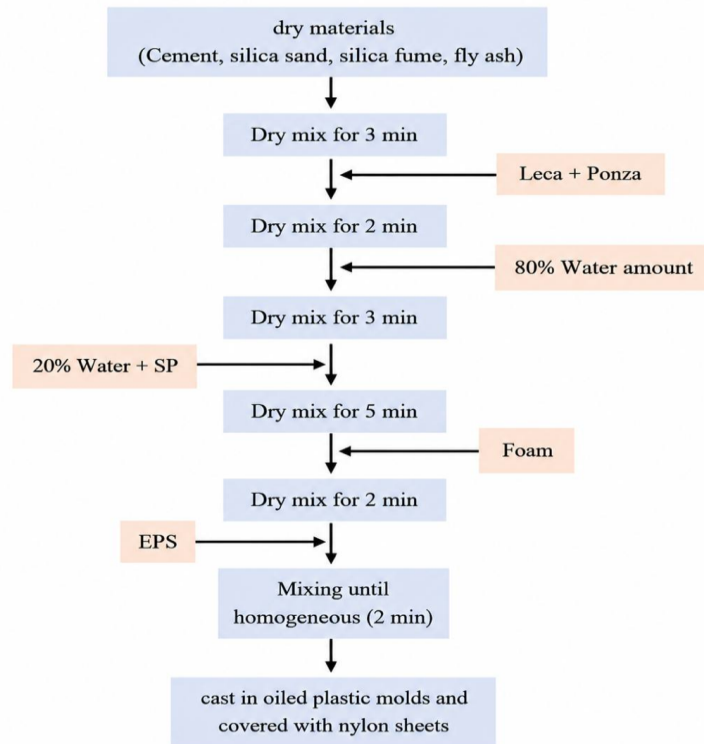


Fig. 3. Flowchart of manufacturing production

4. Tests and Responses

4.1 Density

For all investigated mixes, the density (kg/m³) was calculated as the ratio of dry mass (kg) to specimen volume (m³). Fresh density was measured (to verify the target design density) immediately after mixing process in accordance with ASTM C138/C138M [35] by determining the mass of fresh concrete, whereas dry density was determined in accordance with ASTM C642 [36] by measuring the mass of dry concrete at the testing age by taking average density of three readings for each age.

4.2 Compressive Strength

The compressive strength is the main indicator for evaluating the mechanical performance of concrete. Compressive strength test was carried out on 100 mm cubes, and the average of three specimens was recorded at 28 days of age according to ASTM C495 [37].

4.3 Flexural Strength

Flexural tensile strength (modulus of rupture) which is also known as center-point load test, was carried out on prismatic (40×40×160) mm according to ASTM C348-21 [53]. The average of three readings was taken.

4.4 Thermal Conductivity

Thermal conductivity of concrete (λ) is a ratio of heat flow to the temperature gradient and is expressed in W/m·K. The test was conducted in accordance ASTM C1113 [38]. At 28 days, two specimens of 50×50×30 mm cut from the center of a 100 mm cube were used after drying them in an oven at 60°C for 24 hours until constant weight. As shown in Figure 4.

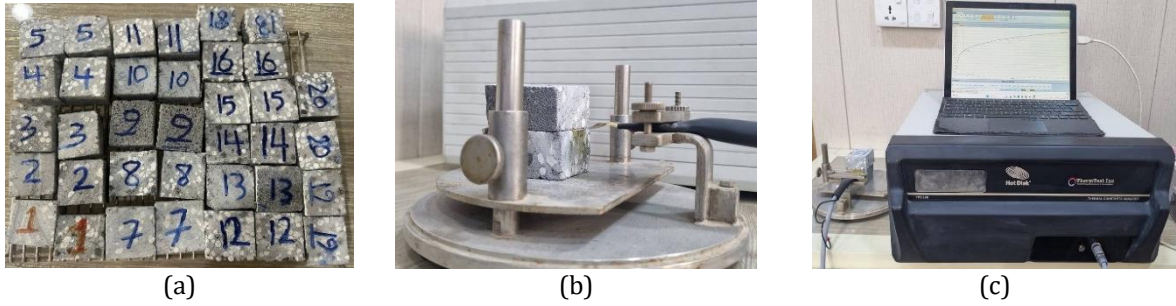


Fig. 4. Thermal conductivity testing: (a) Prepared specimens (b) Thermal conductivity apparatus (c) Data acquisition and processing system

5. Results and Discussion

5.1 Response Results

Figure 5 shows the prepared mixes and the results obtained from the conducted responses tests.

#	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
	StdOrder	RunOrder	PtType	Blocks	Ponza	Leca	EPS	Density	Compressive strength	Flexural	Thermal conductivity
1	17	1	0	1	9.5	9.5	9.5	1095	8.30	1.61	0.393
2	18	2	0	1	9.5	9.5	9.5	1090	8.10	1.58	0.385
3	15	3	0	1	9.5	9.5	9.5	1100	7.90	1.63	0.395
4	14	4	-1	1	9.5	9.5	19.0	1075	5.80	1.27	0.431
5	2	5	1	1	19.0	0.0	0.0	1170	11.50	2.64	0.525
6	16	6	0	1	9.5	9.5	9.5	1089	8.10	1.57	0.387
7	12	7	-1	1	9.5	19.0	9.5	1139	9.50	1.99	0.574
8	13	8	-1	1	9.5	9.5	0.0	1125	10.70	2.16	0.501
9	1	9	1	1	0.0	0.0	0.0	1024	6.50	1.62	0.386
10	9	10	-1	1	0.0	9.5	9.5	1026	6.10	1.34	0.382
11	6	11	1	1	19.0	0.0	19.0	1125	8.00	1.68	0.494
12	8	12	1	1	19.0	19.0	19.0	1295	16.40	3.81	0.595
13	3	13	1	1	0.0	19.0	0.0	1076	7.40	1.55	0.489
14	7	14	1	1	0.0	19.0	19.0	1011	6.43	1.28	0.428
15	4	15	1	1	19.0	19.0	0.0	1232	12.50	2.65	0.551
16	5	16	1	1	0.0	0.0	19.0	990	5.00	1.20	0.372
17	19	17	0	1	9.5	9.5	9.5	1120	8.20	1.62	0.401
18	11	18	-1	1	9.5	0.0	9.5	1136	9.00	1.78	0.479
19	20	19	0	1	9.5	9.5	9.5	1125	8.50	1.67	0.501
20	10	20	-1	1	19.0	9.5	9.5	1240	11.14	2.62	0.506

Fig. 5. Proportions of experimental mixes obtained from Minitab software and their measured responses

The total number of experiments was determined according to equation (2) [24, 39].

$$\text{No. of experiments} = 2^k + 2k + N_c \quad (2)$$

In this study, three independent variables ($k=3$) were adopted, resulting in 20 experimental mixtures designed using Minitab software within the RSM methodology. These mixes included 14 factorial and axial experiments in addition to 6 experiments at the central point.

The details of these trials, including the actual and coded values, as shown in Figure 5 and 6. The actual values were converted to coded values using equation (3):

$$x_i = \frac{(X_i - X_0)}{\Delta X} \quad (3)$$

Where x_i represents the coded value of the variable, X_i the actual value, X_0 the central point value, and ΔX the step change amount. An axial distance of $\alpha = \pm 1.68$ (select α through number of continuous factor) was adopted to achieve the rotatability property in the design, as well as to provide five levels for each independent variable. The experimental results obtained from these 20 mixtures were then used to develop the response surface models. Density of all tested foamed concrete range between (990-1295) kg/m³. While, for 28-day the compressive strength of the mixes was (5.80-16.40) MPa, the flexural strength (1.27-3.81) MPa and thermal conductivity was from 0.382 to 0.595 W/m.K.

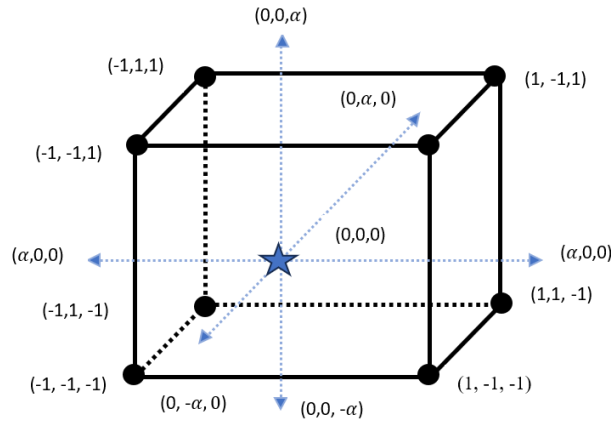


Fig. 6. Design matrix for mixtures using CCD (k=3)[24]

5.2 Selection and Establishing of RSM Models

In this study, for establishing of models, four mathematical models were developed to represent the main responses, which are density, compressive strength, flexural tensile strength and thermal conductivity. These models were created based on the actual values of the responses according to equation (4) where the least squares method was used to estimate the regression coefficients for all terms of the developed models.

$$Y = \beta_0 + \sum_{i=1}^k \beta_i X_i + \sum_{i=1}^k \beta_{ii} X_i^2 + \sum_{i < j}^k \sum_j^k \beta_{ij} X_i X_j + e_i \quad (4)$$

Y: is the predicted response value, X_i, X_j are the coded values of factor. $\beta_0, \beta_i, \beta_{ii}, \beta_{ij}$ are regression coefficients for first, second and interaction terms, respectively, while e_i is random experimental error (residual error). k is number of independent variables. Regression analysis using the Backward elimination procedure showed that the developed models can be adequately represented using second-order polynomial models. This method was used to determine the extent of each independent variable's contribution and its degree of influence on the response. Subsequently, Analysis of Variance (ANOVA) was used to verify the significance of the models and their statistical efficiency. Finally, the modified final forms of the mathematical models were obtained as shown in equations (5-8) as follows:

$$\text{Density} = 1009.7 + 7.75 \text{ Ponza} + 1.15 \text{ Leca} + 0.220 \text{ Ponza} * \text{Leca} \quad (5)$$

$$\begin{aligned} \text{Compressive strength} \\ = 7.761 + 0.2029 \text{ Ponza} - 0.266 \text{ Leca} - 0.1777 \text{ EPS} \\ + 0.01040 \text{ Leca} * \text{Leca} + 0.00979 \text{ Ponza} * \text{Leca} + 0.01098 \text{ Leca} \\ * \text{EPS} \end{aligned} \quad (6)$$

$$\begin{aligned} \text{Flexural} = & 1.850 - 0.0344 \text{ Ponza} - 0.0331 \text{ Leca} - 0.0444 \text{ EPS} \\ & + 0.00389 \text{ Ponza} * \text{Ponza} + 0.00295 \text{ Ponza} * \text{Leca} + 0.00314 \text{ Leca} \\ & * \text{EPS} \end{aligned} \quad (7)$$

$$\begin{aligned} \text{Thermal conductivity} = & 0.3898 + 0.00646 \text{ Ponza} - 0.00885 \text{ Leca} + 0.000677 \text{ Leca} \\ & * \text{Leca} \end{aligned} \quad (8)$$

Where Ponza (X1), Leca (X2), and EPS (X3) represent the input variables, while Density: Y1, Compressive strength: Y2, Flexural: Y3 and Thermal conductivity: Y4 represent output (responses).

5.3 Verification and Modification of RSM Models

ANOVA was conducted to assess the significance and adequacy of the developed regression models and to determine the contribution of the input parameters to the studied responses. The results indicated that most of the model terms were statistically significant, while some interaction and quadratic terms were not significant and were therefore excluded to improve the model's accuracy.

Table 3. Analysis of variance for density quadratic model

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Contribution %
Density model	3	100069	33356.3	38.99	0.000	87.97
Linear	2	96909	48454.5	56.64	0.000	85.19
Ponza	1	87422	87422.5	102.19	0.000	76.85
Leca	1	9486	9486.4	11.09	0.004	8.34
2-Way Interaction	1	3160	3160.1	3.69	N.S.**	2.78
Ponza*Leca	1	3160	3160.1	3.69	N.S.**	2.78
Error	16	13688	855.5			12.03
Lack-of-Fit	11	12477	1134.2	4.68	0.050	10.97
Pure Error	5	1211	242.2			1.06
Total	19	113757				100.00
R-square	87.97%					
R-Squared. Adj	85.71%					

Table 4. Analysis of variance for compressive strength quadratic model

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Contribution %
Compressive strength model	6	117.350	19.5583	14.37	0.000	86.90
Linear	3	98.833	32.9442	24.21	0.000	73.19
Ponza	1	79.017	79.0172	58.07	0.000	58.51
Leca	1	14.957	14.9573	10.99	N.S.**	11.08
EPS	1	4.858	4.8581	3.57	N.S.**	3.60
Square	1	4.409	4.4086	3.24	N.S.**	3.26
Leca*Leca	1	4.409	4.4086	3.24	N.S.**	3.26
2-Way Interaction	2	14.109	7.0544	5.18	0.022	10.45
Ponza*Leca	1	6.248	6.2481	4.59	0.052	4.63
Leca*EPS	1	7.861	7.8606	5.78	0.032	5.82
Error	13	17.689	1.3607			13.10
Lack-of-Fit	8	17.481	2.1851	52.44	0.000	12.95
Pure Error	5	0.208	0.0417			0.15
Total	19	135.039				100.00
R-square	86.90%					
R-Squared. Adj	80.85%					

The coefficients of determination (R^2) for density, compressive strength, flexural strength, and thermal conductivity were found to be 87.97%, 86.90%, 87.09%, and 73.95%, respectively, as shown in Tables 3–6. These results indicate a generally good agreement between the experimental

and predicted values. However, model adequacy was further evaluated using the ANOVA, Lack-of-Fit test, and residual diagnostics. The results of the response surface analysis showed that the coefficient of determination (R^2) for thermal conductivity was 73.95, indicating that the developed model explained a substantial proportion of the variability in the experimental data. The Adjusted R^2 and Predicted R^2 were 69.07% and 63.07%, respectively, with a difference of only 6.00% (0.06) between them. This difference is well below the 0.20 criterion recommended for reasonable agreement between the Adjusted R^2 and Predicted R^2 [40], supporting the adequacy and predictive capability of the developed model. Furthermore, the ANOVA results indicated that the model was statistically significant (P -value < 0.001), while the Lack-of-Fit was not significant ($P = 0.727 > 0.05$), further confirming the suitability of the model [41]. The relatively lower R^2 value obtained for thermal conductivity compared with the other responses may be attributed to the complex nature of heat transfer in lightweight concrete and the influence of several factors, including density, porosity, moisture content, aggregate characteristics, and air-void structure [42–43].

Table 5. Analysis of variance for flexural quadratic model

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Contribution %
Flexural model	6	6.68344	1.11391	14.62	0.000	87.09
Linear	3	4.85621	1.61874	21.25	0.000	63.28
Ponza	1	4.10881	4.10881	53.93	0.000	53.54
Leca	1	0.55696	0.55696	7.31	0.018	7.26
EPS	1	0.19044	0.19044	2.50	N.S.**	2.48
Square	1	0.61600	0.61600	8.09	0.014	8.03
Ponza*Ponza	1	0.61600	0.61600	8.09	0.014	8.03
2-Way Interaction	2	1.21123	0.60561	7.95	0.006	15.78
Ponza*Leca	1	0.56711	0.56711	7.44	0.017	7.39
Leca*EPS	1	0.64411	0.64411	8.45	0.012	8.39
Error	13	0.99041	0.07619			12.91
Lack-of-Fit	8	0.98388	0.12299	94.12	0.000	12.82
Pure Error	5	0.00653	0.00131			0.09
Total	19	7.67385				100.00
R-square	87.09%					
R-Squared. Adj	81.14%					

Table 6. Analysis of variance for thermal conductivity quadratic model

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% Contribution
Model	3	0.07088	0.023627	15.14	0.000	73.95
Linear	2	0.05222	0.026108	16.73	0.000	54.48
Ponza	1	0.03770	0.037700	24.16	0.000	39.33
Leca	1	0.01452	0.014516	9.30	0.008	15.15
Square	1	0.01867	0.018666	11.96	0.003	19.48
Leca*Leca	1	0.01867	0.018666	11.96	0.003	19.48
Error	16	0.02497	0.001560			26.05
Lack-of-Fit	11	0.01494	0.001358	0.68	0.727	15.59
Pure Error	5	0.01003	0.002006			10.46
Total	19	0.09585				100.00
R-square	73.95%					
R-Squared. Adj	69.07					

Therefore, part of the unexplained variation may be associated with factors that were not explicitly incorporated into the present statistical model. Accordingly, the obtained R^2 value of 73.95% can be considered acceptable when evaluated in conjunction with the close agreement between the

Adjusted R^2 and Predicted R^2 , the statistically significant ANOVA result, and the non-significant Lack-of-Fit. Thus, the relatively lower R^2 does not necessarily indicate inadequate model performance, but may instead reflect the complex nature of thermal conductivity and the multiple factors influencing heat transfer in lightweight concrete [40, 44].

The backward elimination procedure was performed using α -to-remove = 0.10; therefore, terms with P-values between 0.05 and 0.10 were retained in the final models, although they were considered statistically non-significant at the 5% level. The Lack-of-Fit of the density model ($P = 0.050$) was considered borderline and was therefore interpreted cautiously. For compressive strength, the Lack-of-Fit was significant ($P < 0.001$), indicating that the model did not fully capture all variability in the experimental response. Nevertheless, the overall regression model was significant ($P < 0.001$), with R^2 and adjusted R^2 values of 86.90% and 80.85%, respectively. The significant Lack-of-Fit may partly reflect the heterogeneous nature of lightweight foamed concrete, where variations in the distribution of lightweight aggregates with different pore structures and foam-generated air voids may introduce variability that is not fully captured by the model. Therefore, the compressive strength model was retained for evaluating the investigated factor effects within the studied experimental domain, while the significant Lack-of-Fit was explicitly recognized as a limitation when interpreting the model results. The final analysis of the modified models showed that the studied properties can be arranged according to the degree of effect of the input variables on the resulting responses as follows:

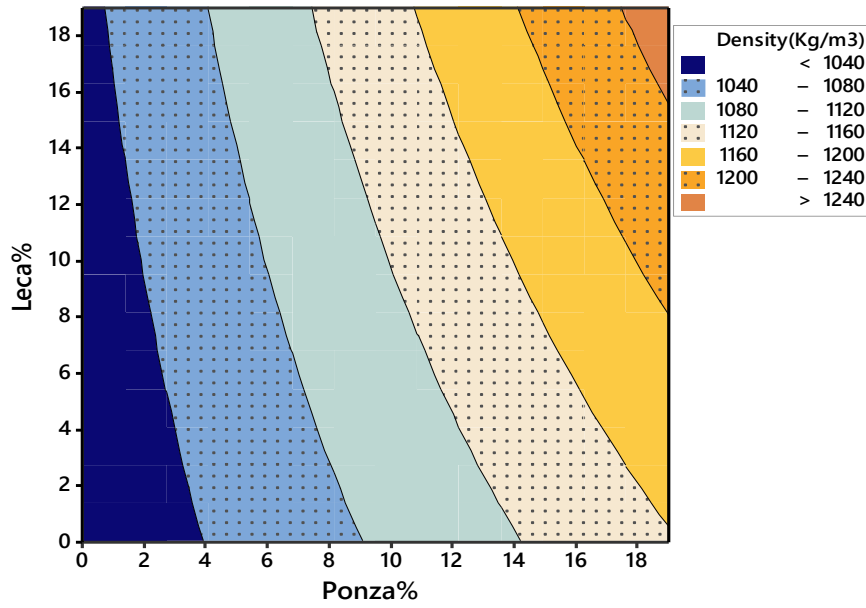
- Density: - the ranking of the influential variables was as follows (Ponza > Leca > Ponza $\times$ Leca). Where the Ponza variable showed the greatest effect on density compared to the other variables.
- Compressive Strength: - the ranking of the influential variables was as follows (Ponza > Leca > Leca $\times$ EPS > Ponza $\times$ Leca > EPS > Leca $\times$ Leca). Where the Ponza variable had the greatest effect on compressive strength, while the effect of the EPS variable was less significant compared to the other variables.
- Flexural Strength: - the ranking of the influential variables was as follows (Ponza > Leca $\times$ EPS > Ponza $\times$ Ponza > Ponza $\times$ Leca > Leca > EPS). Where the Ponza variable showed the greatest effect on flexural strength compared to the other variables.
- Thermal Conductivity: - the ranking of the influential variables was as follows (Ponza > Leca $\times$ Leca > Leca). Where the Ponza variable had the greatest effect on the thermal conductivity coefficient compared to the other variables. Thermal conductivity is inversely related with thermal insulation, so the Ponza variable had the lowest effect on the thermal insulation.

A detailed additional discussion will be provided on the effect of individual and interaction variables on the studied properties.

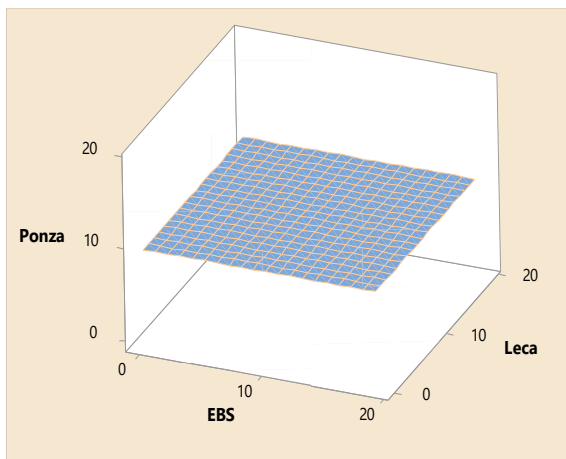
5.4 Effect of Input Parameters

Analyzing the effect of lightweight aggregate ratios on the properties of lightweight foam concrete is important for understanding the behavior of the developed mixes. The individual and combined effects of Ponza, Leca and EPS on density, compressive strength, flexural strength, and thermal conductivity were evaluated based on the results of regression analysis. To this end, contour plots and three-dimensional surface plots were generated to illustrate the relationship between the input variables and the studied responses. The contour plot for density shown in Figure 7a illustrates the interaction between the ratios of Leca and Ponza on density, where it is observed that increasing the Leca ratio leads to a slight decrease in density compared to Ponza, due to the lower specific weight and higher porosity of Leca particles. The porous structure of Leca contains numerous internal air-filled voids, which reduce the amount of solid material per unit volume and consequently contribute to the reduction in concrete density [4]. The surface plots in Figure 7b and c also show the combined effect of both Leca and Ponza and EPS on density, where the results indicate that increasing the EPS content leads to a significant decrease in density due to its lower bulk density compared to the lightweight aggregate [45]. This reduction is mainly associated with the cellular structure of EPS, which contains a large volume of enclosed air and therefore introduces more low-density regions into the concrete matrix [15].

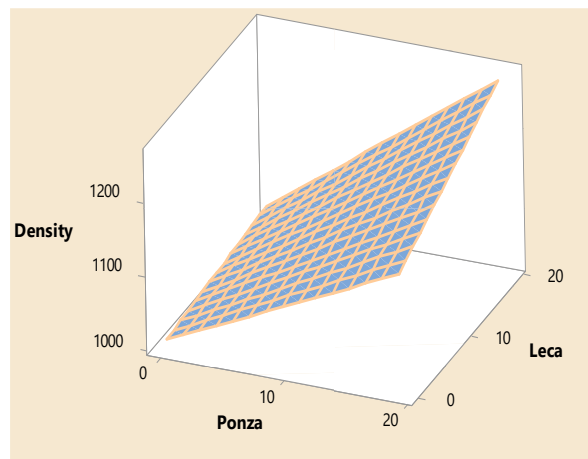
The density values ranged from approximately 990 to 1295 kg/m³ depending on the variations in the lightweight aggregate ratios in the mixes. The compressive strength contour plot in Figure 8a shows the interaction between the ratio of Leca and Ponza lightweight aggregates on the compressive strength where it can be observed that increasing the ratio of Ponza leads to an improvement in compressive strength compared to Leca [45]. This is due to the higher Ponza hardness and better mechanical bonding within the cement paste. The rough and irregular surface of Ponza can also enhance mechanical interlocking with the cement paste, resulting in more effective stress transfer through the aggregate–matrix system [19]. The surface graphs in Figure 8b and c also show the combined effect of Ponza, Leca and EPS on the compressive strength where the results show that increasing the EPS content leads to a decrease in the compressive strength due to its lower hardness and weaker bond compared to the light mineral additive [19, 46]. In addition, the low stiffness of EPS limits its ability to transfer applied loads efficiently to the surrounding cementitious matrix, which contributes to the reduction in compressive strength [15]. The compressive strength value varied between about 5 MPa and 16.4 MPa depending on the difference in the amount and type of added LWA in the mixes.



(a)

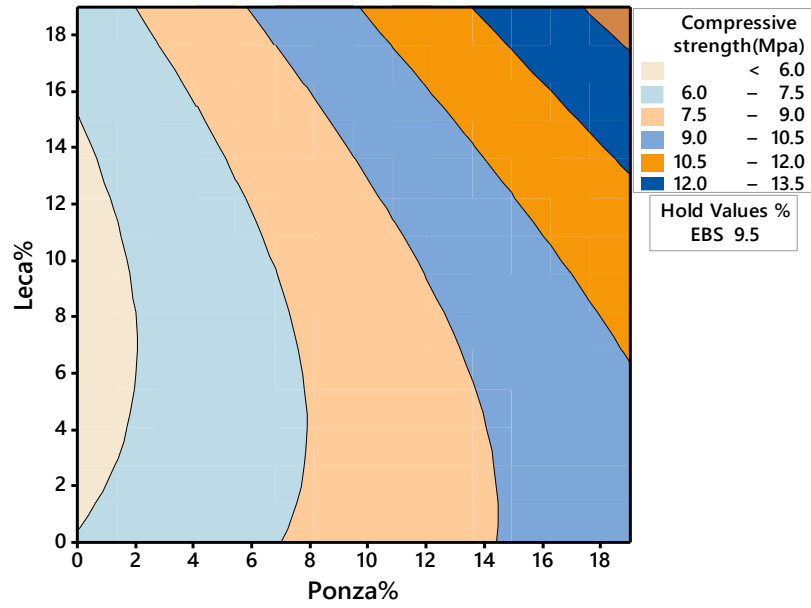


(b)

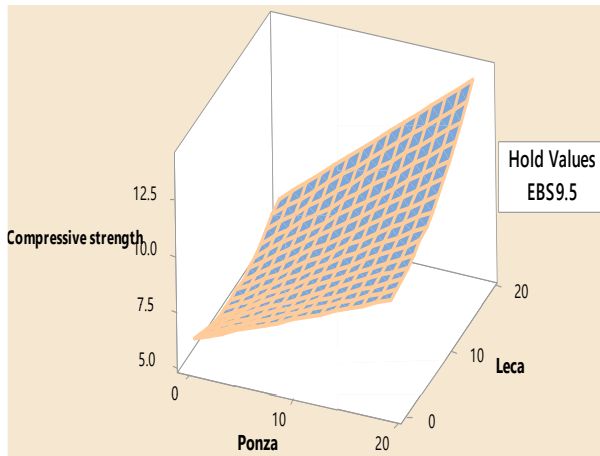


(c)

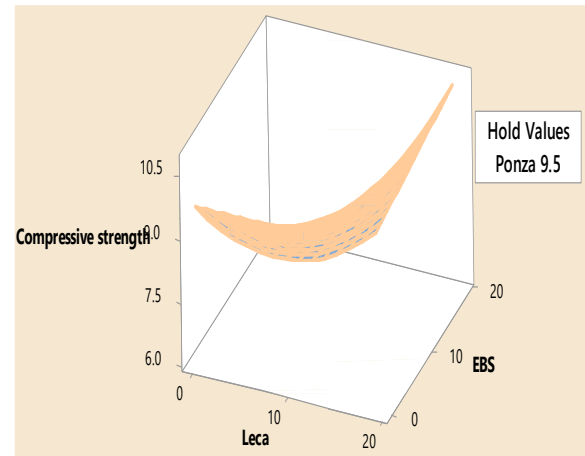
Fig. 7. Effect of LWA ratio on density: (a)Contour plot of density Vs Leca, Ponza, (b) Surface Plot of Ponza vs Leca, EPS, (c) Surface plot of density vs Leca, Ponza



(a)



(b)

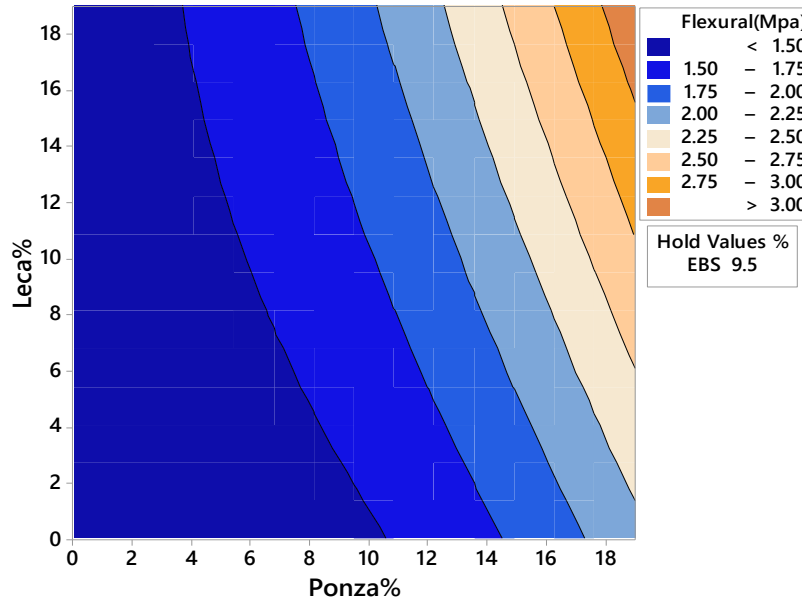


(c)

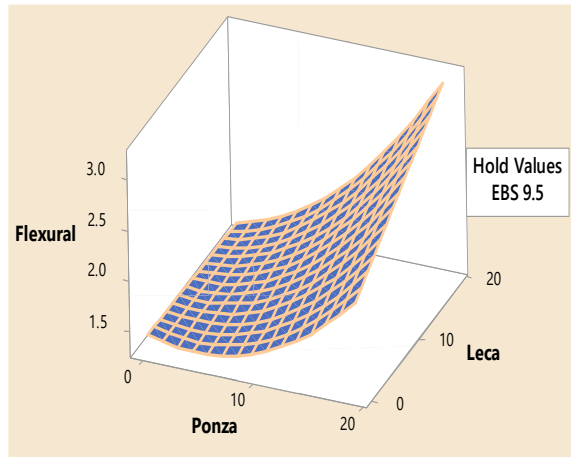
Fig. 8. Effect of LWA ratio on compressive strength: (a) Contour plot of compressive strength Vs Leca, Ponza, (b) Surface plot of compressive strength vs Leca, Ponza, (c) Surface plot of compressive strength vs EPS, Leca

The flexural strength contour plot in Figure 9a shows the interaction between Leca and Ponza ratios on flexural strength where it can be observed that increasing the Ponza ratio leads to an improvement in flexural strength compared to Leca. This is due to the enhanced bonding between the aggregate particles and the cement matrix. The improved mechanical interlocking and stress transfer at the aggregate–matrix interface can help the concrete resist the tensile stresses developed during flexural loading [11, 19]. Furthermore, the surface plots in Figure 9b and c show the effect of both Leca and EPS on the flexural strength where the results show that increasing the proportion of EPS leads to a slight decrease in the flexural strength due to the lower hardness of this type of addition [47]. This behavior can be attributed to the relatively low stiffness of EPS, which reduces its contribution to load transfer within the cementitious matrix [15]. The highest value of the flexural strength was about 3.81 MPa based on the change in the amount and type of added LWA. The thermal conductivity contour plot shown in Figure 10a illustrates the mutual effect of the proportions of Ponza and Leca on thermal conductivity, where it is observed that increasing the proportion of Ponza leads to a decrease in thermal conductivity due to its porous structure and low heat transfer [45, 47]. The air-filled pores within the porous Ponza structure interrupt continuous heat-transfer paths through the solid phase, thereby increasing thermal resistance and reducing thermal conductivity [11].

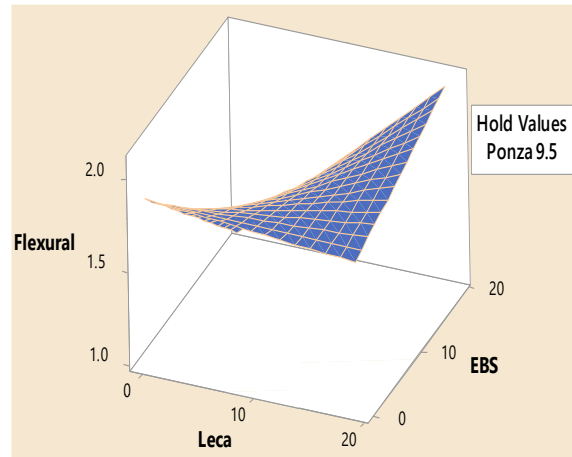
The surface plot in Figure 10b also shows the combined effect of Ponza, Leca, and EPS on thermal conductivity. The results indicate that increasing the EPS content significantly decrease thermal conductivity. This reduction can be attributed to the closed-cell structure and excellent insulating properties [19]. The closed air-filled cells of EPS limit heat transfer through the material and provide additional thermal resistance, resulting in lower thermal conductivity [15]. The thermal conductivity values ranged between approximately 0.595 and 0.372 W/m·K depending on the variations in the lightweight aggregate ratios and type. In general, the results confirm that natural lightweight aggregates such as Ponza contribute positively to improving mechanical properties, while both Leca and EPS play an important role in reducing density and thermal conductivity, making the produced mixes suitable for use in semi-structural lightweight concrete and thermal insulation applications.



(a)



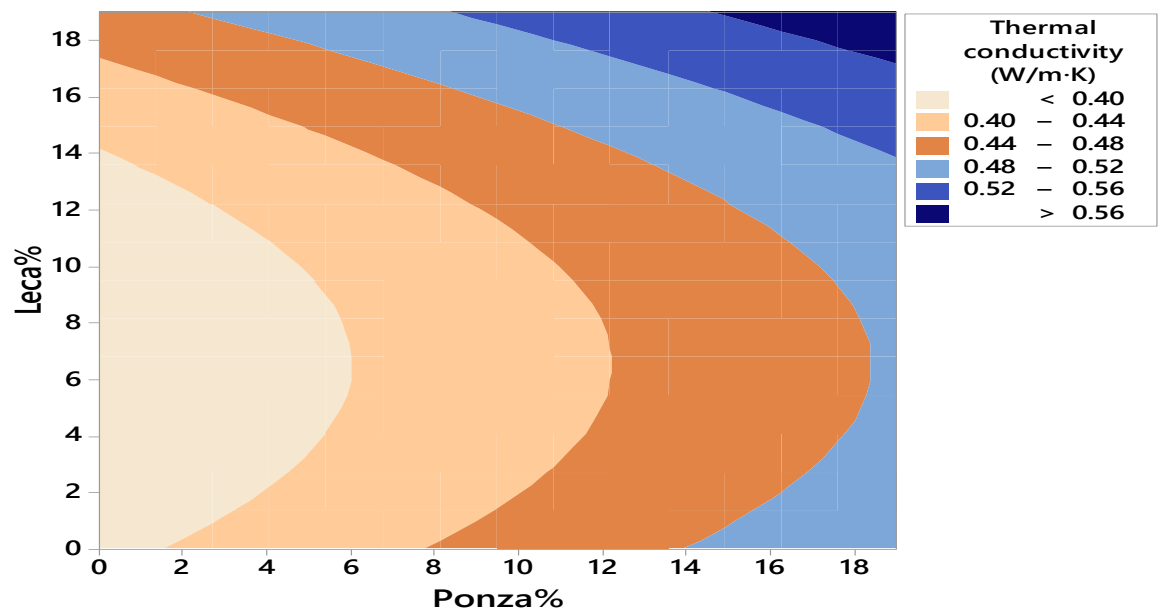
(b)



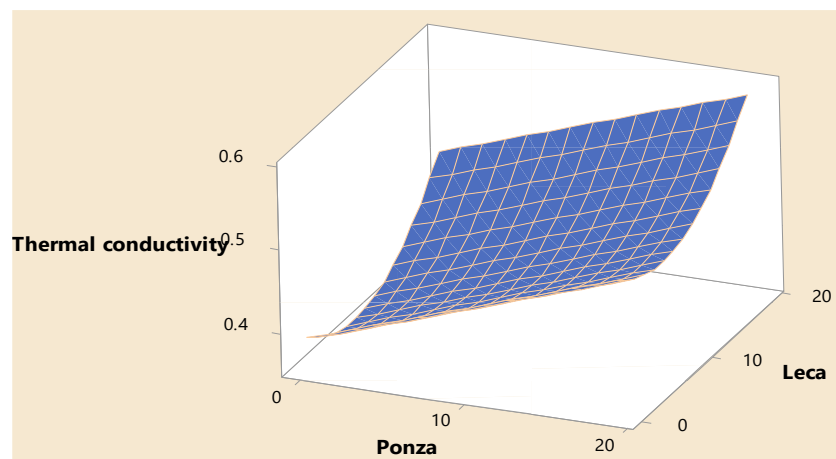
(c)

Fig. 9. Effect of LWA ratio on flexural (a) Contour plot of flexural Vs Leca, Ponza, (b) Surface plot of flexural vs Leca, Ponza, (c) Surface plot of flexural vs EPS, Leca

Normal probability plots of the residuals were used to assess the fit of the developed regression models. As shown in Figure 11, the residual points tend to align with the reference straight line without any obvious systematic deviations, indicating that the residuals approximately follow a normal distribution [48]. Figure 12 also shows residuals versus fitted values plots, where the residuals appear randomly distributed around the zero line without any clear pattern or consistent curvature.

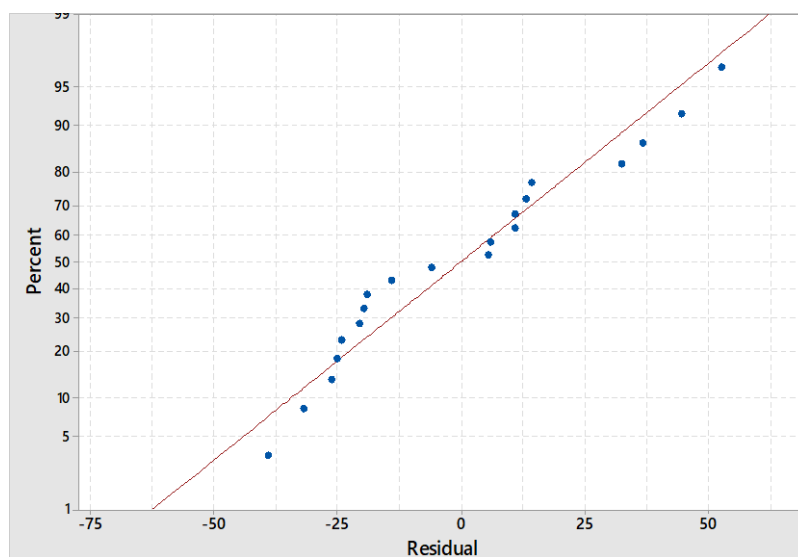


(a)

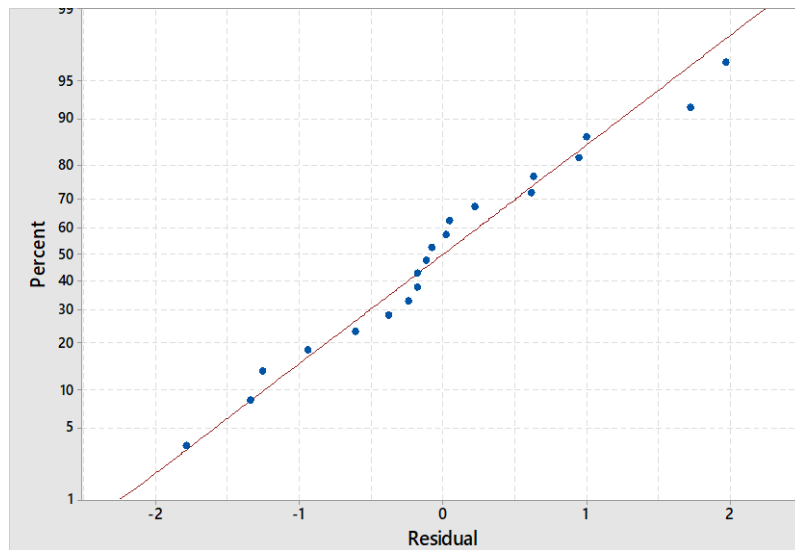


(b)

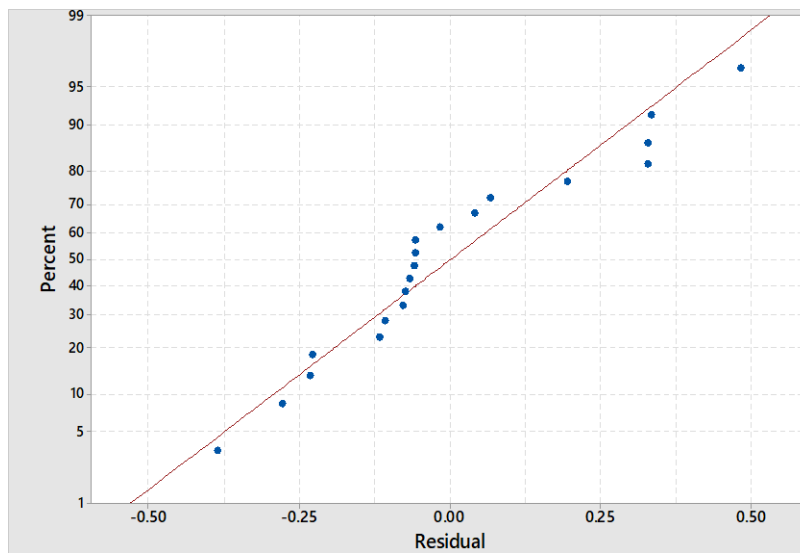
Fig. 10. Effect of LWA ratio on thermal conductivity (a) Contour plot of thermal conductivity Vs Leca, Ponza, (b) Surface plot of thermal conductivity vs Leca, Ponza



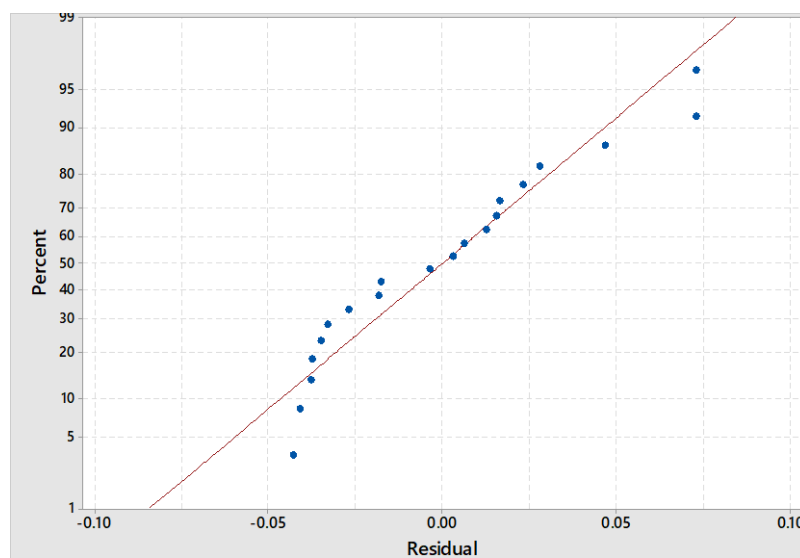
(a)



(b)

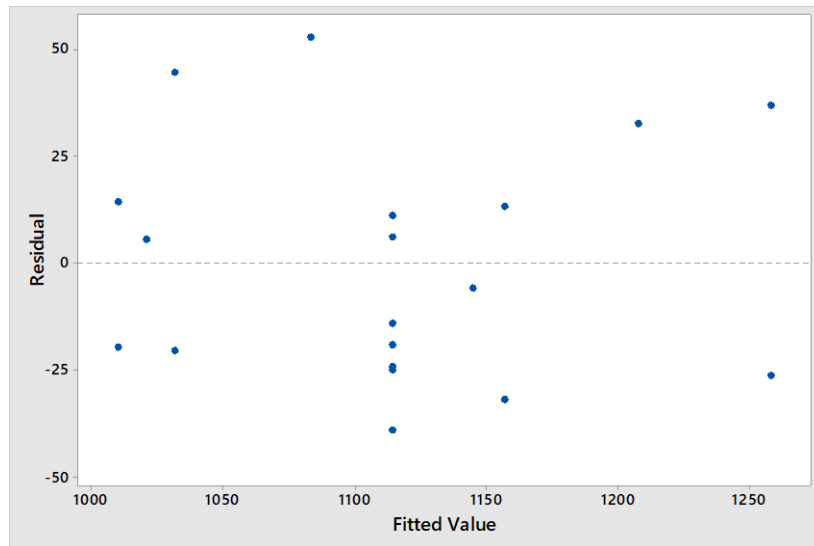


(c)

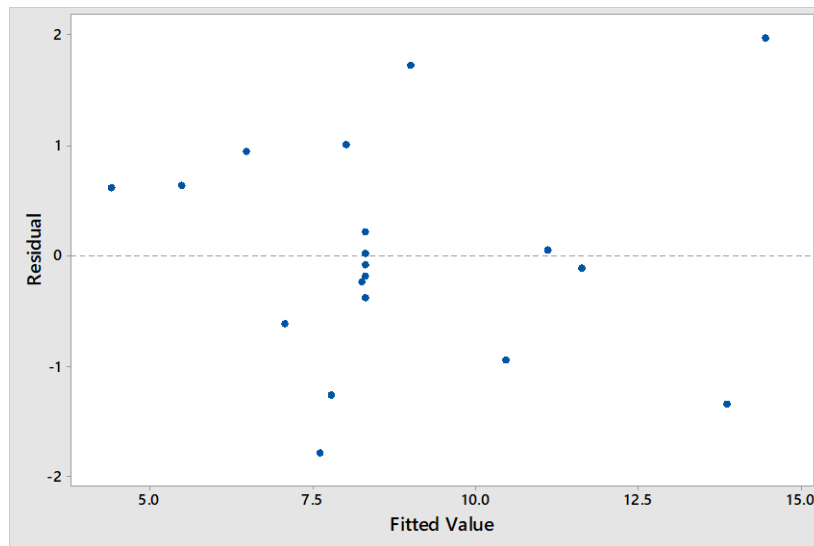


(d)

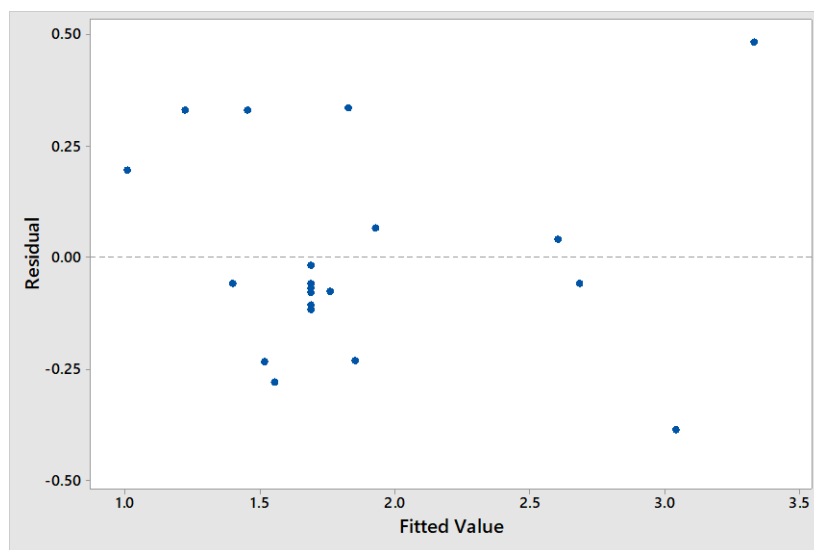
Fig. 11. Normal probability plot of residuals for the (a) Density, (b) Compressive strength, (c) Flexural, (d) Thermal conductivity



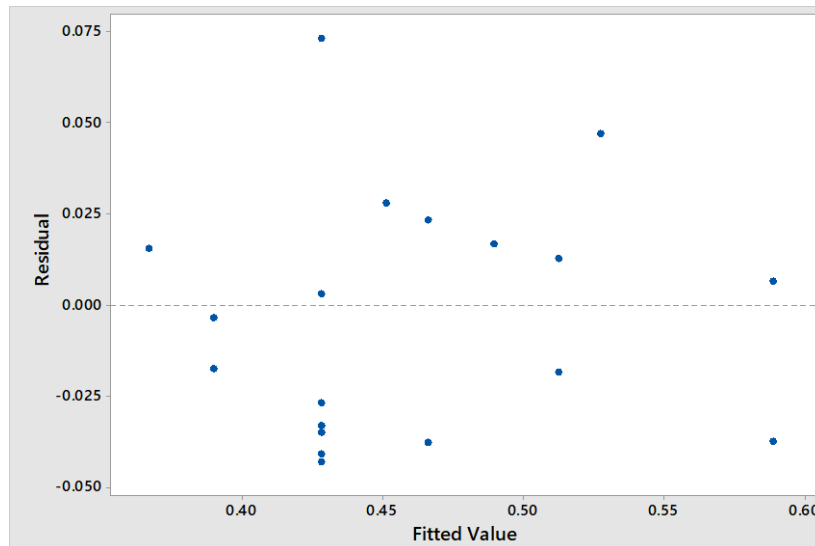
(a)



(b)



(c)



(d)

Fig. 12. Residuals versus fitted values for the (a) Density, (b) Compressive strength, (c) Flexural, (d) Thermal conductivity

This suggests there is no clear violation of the constant variance assumption and supports the fit of the developed models to the experimental data. Overall, the residual diagnostics showed acceptable residual behavior for the developed models; however, these results were interpreted together with the ANOVA and Lack-of-Fit results.

5.5 Responses Optimization

In this study, optimization was carried out using Minitab 17 software by maximizing or minimizing the Desirability Function for all responses to determine the optimal values of the studied variables [49]. During the numerical optimization process, the optimal mixture proportions were 17.8485% Ponza, 4.2222% Leca and 0% EPS.

The optimization aimed to maximize compressive and splitting tensile strength while minimizing density and thermal conductivity. These criteria were selected to achieve a balance between mechanical performance and thermal conductivity. The selection of the numerical optimization program (Response Optimization) for these ratios is not random, but rather depends on achieving the best balance among all the required responses. Therefore, the program preferred Ponza of 17.8485%, Leca of 4.2222%, and EPS of 0% for the following reasons. Ponza is a porous and lightweight material, but it has better adhesion with cement paste compared to EPS, which helps to relatively improve compressive strength, maintain low density, reduce thermal conductivity due to its porous nature [50]. Therefore, the program gave it a higher rating to achieve a balance between strength and insulation. While, Leca is characterized by higher mechanical strength than most lightweight aggregates, closed porous structure that helps reduce thermal conductivity [19, 50], improved split tensile strength due to increased internal structure bonding. For this reason, it has been used in limited but effective amounts to improve mechanical properties without significantly increasing density [51].

The numerical optimization program excluded EPS from the optimal mix. Although EPS provides high efficiency in thermal insulation, it has lower mechanical performance than Ponza and Leca. Its use resulted in lower compressive strength and splitting tensile strength. In addition, its smooth surface and low cohesion may lead to weaker bonding with the cement matrix [50, 52]. Therefore, its negative effect on mechanical properties outweighed its thermal insulation benefit under the applied optimization criteria.

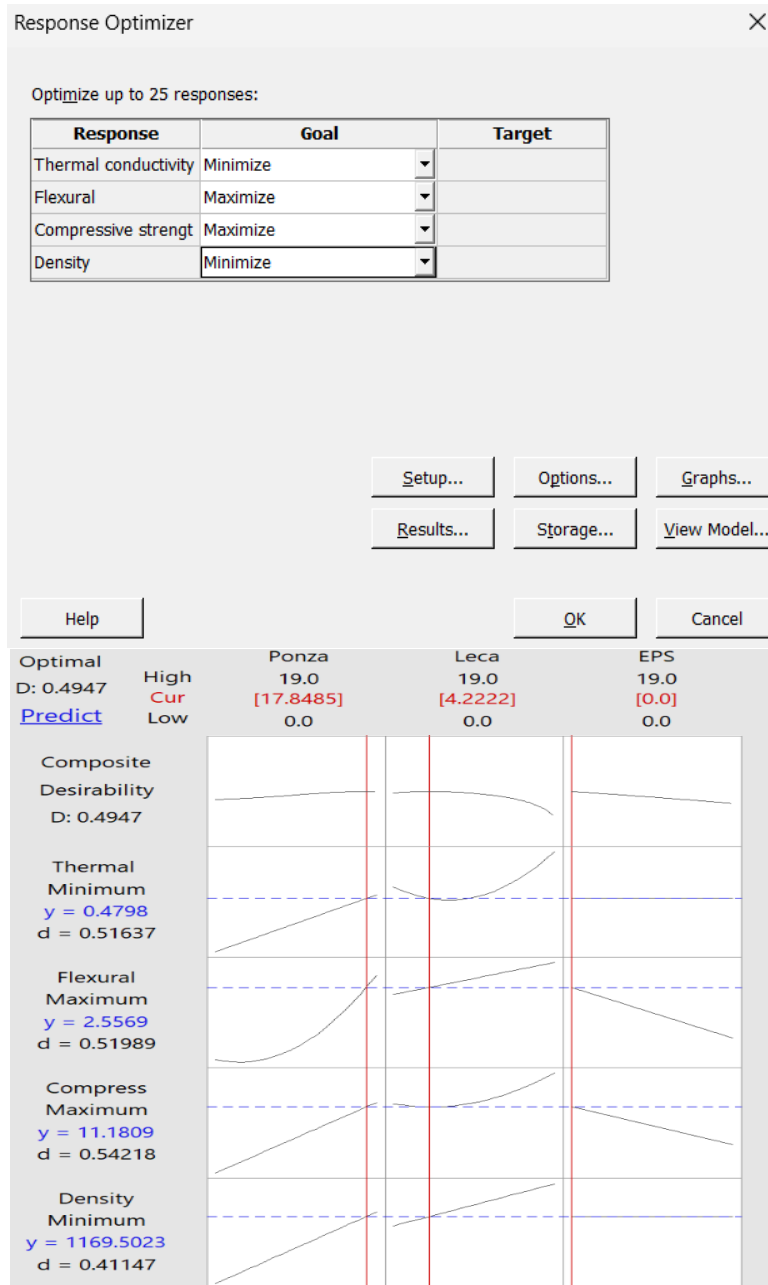


Fig. 13. Optimization criteria and optimum mix results

Instead, the program preferred to rely on foam voids (entrained air voids) because it effectively reduces density and thermal conductivity through a uniform and consistent distribution of voids within the foam concrete provides: homogeneous distribution of voids, better stability than granular materials, less negative impact on strength compared to lightweight aggregate [5]. This makes it more balanced choice for achieving the highest compressive strength and highest splitting tensile strength while maintaining the lowest density and best thermal insulation simultaneously [14].

The optimum mixture was experimentally prepared and tested independently after completing the RSM optimization process. The experimental results of this mixture were not included in the dataset used to develop the RSM models. As shown in Fig. 14, good agreement was observed between the predicted and experimental results for density, compressive strength, flexural strength, and thermal conductivity, with percentage errors of approximately 0.81%, 1.05%, 3.52%, and 3.83%, respectively. The low prediction errors confirm the reliability of the developed models in predicting the responses of the optimum mixture.

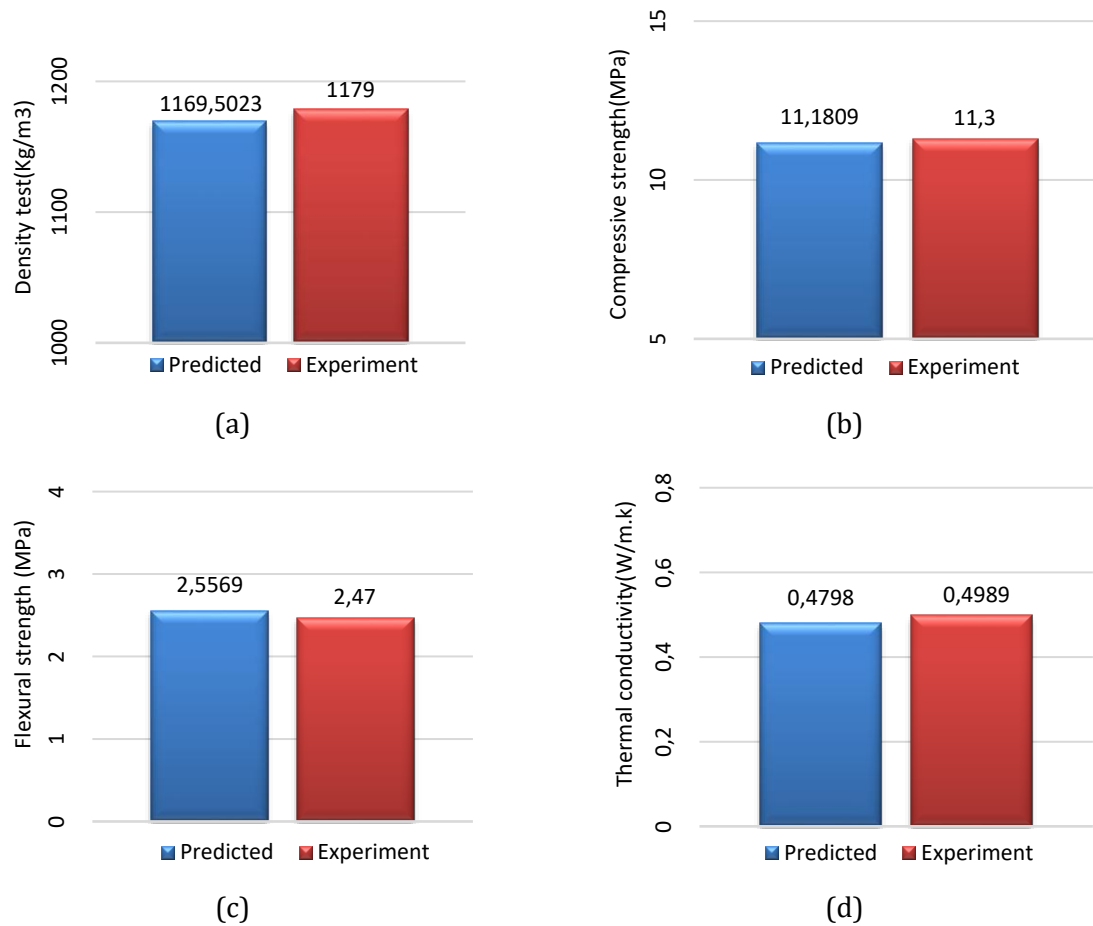


Fig. 14. Comparison between the RSM-predicted and independently measured experimental values for the optimum mixture, for (a) Density, (b) Compressive strength, (c) Flexural strength, and (d) Thermal conductivity

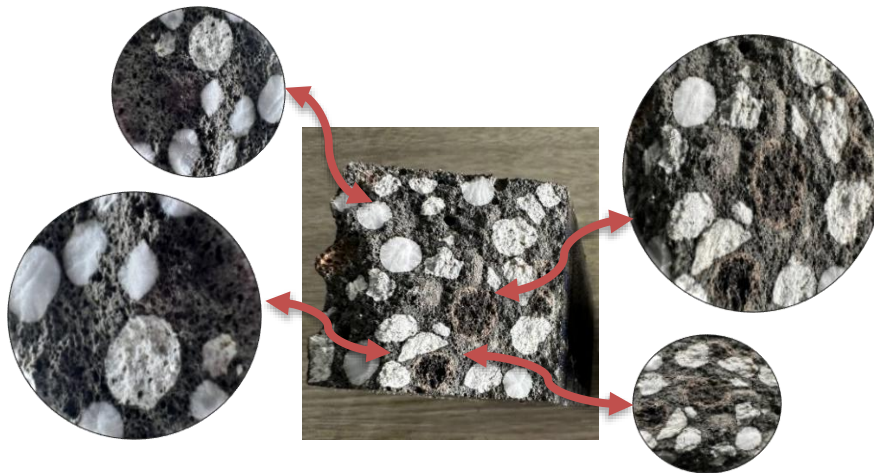


Fig. 15. Distribution of hybrid LWA in foam concrete

6. Conclusion

In this study, a comprehensive experimental and statistical investigation was conducted to evaluate and improve the performance of foam concrete by adding hybrid lightweight aggregates, which include Ponza, Leca, and Expanded Polystyrene (EPS), utilizing the RSM based on CCD. The main objective was to achieve an optimal balance between mechanical properties and thermal performance while maintaining low density. The experimental results showed that the density of

the lightweight foam concrete mixes ranged from 990 to 1295 kg/m³, indicating successful production of lightweight concrete within the required classifications. Compressive strength ranged from 5.80 to 16.40 MPa, while flexural strength ranged from 1.27 to 3.81 MPa. Additionally, the thermal conductivity values ranged from 0.382 to 0.595 W/m·K, confirming the suitability of this concrete for thermal insulation applications.

Statistical modeling using the RSM methodology demonstrated good predictive performance. The developed quadratic models showed good agreement with the experimental results. Analysis of variance showed that Ponza was the most influential factor on all studied properties, particularly density and mechanical strength. Increasing its content improved compressive and flexural strength due to its better bonding ability with the cement paste. In contrast, lightweight aggregate contributed to reducing density and thermal conductivity while maintaining acceptable mechanical performance. EPS had a clear effect in reducing density and thermal conductivity, but it negatively affected mechanical properties due to weak cohesion and low stiffness. Therefore, different lightweight aggregates were combined (hybrid) to achieve the best possible performance. The interaction effects between the investigated variables played a significant role in determining the overall performance of the lightweight foam concrete mixes. The interaction between Ponza and Leca contributed to the improvement of both strength and density, as shown by the contour and surface plots in Figures 7 and 8, while the interaction involving EPS led to a reduction in mechanical performance. This confirms the importance of achieving a precise balance between different lightweight aggregate proportions to obtain the best possible performance. The optimization process using the desirability function showed that the optimal mix proportions are approximately 17.85% Ponza, 4.22% Leca, and 0% EPS. This mix achieved a balanced performance characterized by improved mechanical properties, reduced density, and enhanced thermal insulation. The exclusion of EPS from the optimal mix indicates that its negative effect on strength outweighs its thermal benefit under the applied optimization conditions. Finally, the validation results showed good agreement between the experimental and predicted values, confirming the reliability of the RSM methodology as an effective tool for designing and optimizing foamed concrete mixes using hybrid lightweight aggregates. In general, this study demonstrates that combining multiple types of lightweight aggregate with advanced statistical optimization techniques is an effective approach to producing lightweight foamed concrete for semi-structural and thermal insulation applications.

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