

Optimization of Mechanical Properties and Quality Index of Perlite Lightweight Concrete Reinforced with Microsilica and Glass Wool Fibers Using Response Surface Methodology

Hooman Yaghibipour , Hamidreza Tavakoli * 

Department of Civil Engineering, Babol Noshirvani University of Technology, Babol, Iran

ARTICLE INFO

Article history:

Received 05 July 2026

Revised 24 August 2026

Accepted 13 September 2026

Available online 01 July 2027

Keywords:

Perlite lightweight concrete

Microsilica

Glass wool fibers

Compressive strength

Quality index

Response Surface Methodology

ABSTRACT

Perlite lightweight concrete has attracted considerable attention because of its low density and favorable thermal performance. However, its relatively low mechanical strength and brittle behavior still limit its structural applications. This study investigates the combined effects of microsilica content (7.5–12.5%), glass wool fiber dosage (0–1.5 vol%), and fiber length (5–50 mm) on the mechanical properties and quality index of perlite lightweight concrete. A total of 30 concrete mixtures were designed and experimentally tested under compression, and the obtained data were subsequently analyzed using response surface methodology (RSM) to evaluate factor interactions and determine the optimum mixture proportions. Compressive strength tests were conducted on all mixtures, whereas stress-strain behavior was evaluated for 14 representative mixtures selected to characterize the deformation response. Overall, the simultaneous incorporation of microsilica and glass wool fibers improved the compressive strength, ductility, and energy absorption capacity of perlite lightweight concrete. The experimental results demonstrated that the highest compressive strength of 40.0 MPa was achieved for the mixture containing 10% microsilica and 0.5% glass wool fibers with a length of 27.5 mm. In contrast, the RSM-based multi-objective optimization identified a different optimum mixture containing approximately 9.4% microsilica and 0.9% glass wool fibers, which yielded the maximum quality index (R/ρ), defined as the compressive strength-to-density ratio, representing the optimum balance between mechanical performance and density. The novelty of this study lies in integrating experimental investigation with RSM-based multi-objective optimization to distinguish between the optimum compressive strength obtained experimentally and the mathematically optimized quality index, thereby providing a practical framework for optimizing both strength and strength-to-density efficiency of structural lightweight concrete.

How to cite this article: Yaghibipour, H. R., Tavakoli, H. Optimization of Mechanical Properties and Quality Index of Perlite Lightweight Concrete Reinforced with Microsilica and Glass Wool Fibers Using Response Surface Methodology. Civil Engineering and Applied Solutions. 2027; 3(3): 1–21. doi:10.22080/ceas.2026.32327.1118.

1. Introduction

In recent decades, the development of high-performance lightweight concrete has received considerable attention as an effective approach for reducing structural dead load and improving thermal performance [1–3]. However, reducing density is often associated with a decline in mechanical strength and durability; therefore, the incorporation of pozzolanic materials and reinforcing fibers has been widely proposed to compensate for these deficiencies. Microsilica, as a highly reactive pozzolanic material, enhances the

* Corresponding author.

E-mail address: tavakoli@nit.ac.ir (H. R. Tavakoli).



cement paste microstructure, reduces porosity, and improves the interfacial transition zone (ITZ) between paste and aggregates, thereby increasing concrete strength and durability. In addition, glass wool fibers improve post-peak behavior, ductility, and energy absorption capacity by controlling microcrack propagation and transferring stresses across crack surfaces [4, 5].

Several studies have investigated the influence of different additives and fibers on concrete performance. Zeyad et al. [6] demonstrated that the use of heavyweight aggregates together with steel, basalt, and bent-fiber reinforcements enhanced both mechanical properties and gamma-ray shielding performance, although their primary focus was radiation protection rather than lightweight concrete optimization. Abdelsalam et al. [7] reported that natural fiber ropes improved crack control and ductility in reinforced concrete beams, although the ultimate load-carrying capacity decreased. Similarly, Dziomdziora and Smarzewski [8] showed that hybrid fiber systems can enhance the mechanical performance and post-cracking behavior of concrete; however, achieving uniform fiber dispersion remains a major challenge.

Standard-based investigations indicate that ASTM (American Society for Testing and Materials) standards do not provide a specific criterion for determining stress reduction levels in energy absorption calculations, and most studies adopt a range between 20% and 80% of peak stress. According to Deng et al. [9], a 50% reduction from peak stress represents a stable and reproducible criterion for evaluating absorbed energy.

Altalib et al. [10], Fallahatabar Shiade and Tavakoli [11], Akbarpour et al. [12], and Tavakoli [13] investigated the effects of pozzolanic materials and different fiber types on the mechanical properties and durability of concrete. Their findings demonstrated that pozzolanic additives significantly improve flexural strength, energy absorption capacity, and concrete performance under elevated temperatures. In addition, these studies evaluated the applicability of intelligent predictive methods and non-destructive techniques, such as ultrasonic pulse velocity, for estimating the properties of fiber-reinforced self-compacting concrete. Despite these advances, previous investigations have generally focused on individual parameters or specific fiber systems rather than simultaneously optimizing microsilica dosage, glass wool fiber content, and fiber length.

Recent studies [14–18] have confirmed this limitation and proposed various approaches to improve the mechanical performance of lightweight concrete. In this regard, microsilica and reinforcing fibers are considered among the most effective approaches for improving post-peak resistance, fracture strain, and energy absorption capacity. Most previous studies have investigated either supplementary cementitious materials or reinforcing fibers individually, whereas limited attention has been paid to their combined interaction in perlite lightweight concrete. Furthermore, previous investigations have rarely considered the simultaneous optimization of microsilica dosage, glass wool fiber content, and fiber length using a statistical multi-objective approach. In addition, distinguishing between the experimentally obtained optimum mechanical performance and the mathematically optimized quality index has not been adequately addressed in the existing literature.

Accordingly, the present study investigates the combined effects of microsilica dosage, glass wool fiber content, and fiber length on the compressive strength, stress-strain behavior, energy absorption capacity, and quality index of perlite lightweight concrete. Response Surface Methodology (RSM) was employed to quantify the interaction between variables and to perform multi-objective optimization. Unlike previous studies, this research distinguishes between the experimentally measured optimum compressive strength and the RSM-predicted optimum quality index, thereby providing a practical framework for proportioning structural lightweight concrete with improved mechanical efficiency.

2. Materials and methods

2.1. Preparation of materials

Microsilica was used as a supplementary cementitious material because of its well-established pozzolanic activity and its beneficial effects on the microstructure and mechanical performance of concrete [19]. Glass wool fibers were incorporated as reinforcement because previous studies have demonstrated their beneficial effects on crack control and the mechanical performance of cementitious composites [20–22]. In the present study, perlite was selected as the lightweight aggregate due to its low density, favorable thermal insulation properties, compatibility with cement paste, and wide availability, making it suitable for producing structural lightweight concrete with acceptable mechanical performance. In the present study, perlite was selected as the lightweight aggregate due to its low density, favorable thermal insulation properties, compatibility with cement paste, and wide availability, making it suitable for producing structural lightweight concrete with acceptable mechanical performance.

For specimen preparation, type II Portland cement, natural coarse aggregate, and lightweight perlite aggregate were used. Lightweight perlite fine aggregate complied with ASTM C330/C330M-23 [23], while coarse aggregates satisfied ASTM C33/C33M-18 [24] requirements. Aggregate gradation was modified according to the standard limits, and the amounts of perlite and coarse aggregate were adjusted proportionally to maintain a constant total mixture volume with varying microsilica replacement levels. Cylindrical specimens with dimensions of 105 mm × 200 mm were then prepared for compressive strength testing in accordance with ASTM C39 (Fig. 1).

As illustrated in Fig. 2, fine and coarse aggregates were first sieved separately. Dry constituents, including cement, perlite, microsilica, coarse aggregate, and glass wool fibers, were then weighed and mixed, followed by the gradual addition of water and superplasticizer.

2.2. Concrete mixture proportions

The concrete mixture proportions were determined based on ASTM C330/C330M-23 [23], ASTM C567-05a [25], ASTM C496-96 [26], ASTM C469-02 [27], ASTM C39/C39M-21 [28], and ACI 211.2-98 [29] recommendations. The final mixture consisted of approximately 900 kg/m³ coarse aggregate, 250 kg/m³ lightweight fine aggregate, 510 kg/m³ cement, 170 kg/m³ water, and 10 kg/m³ superplasticizer, corresponding to a water-to-cement ratio of 0.335.

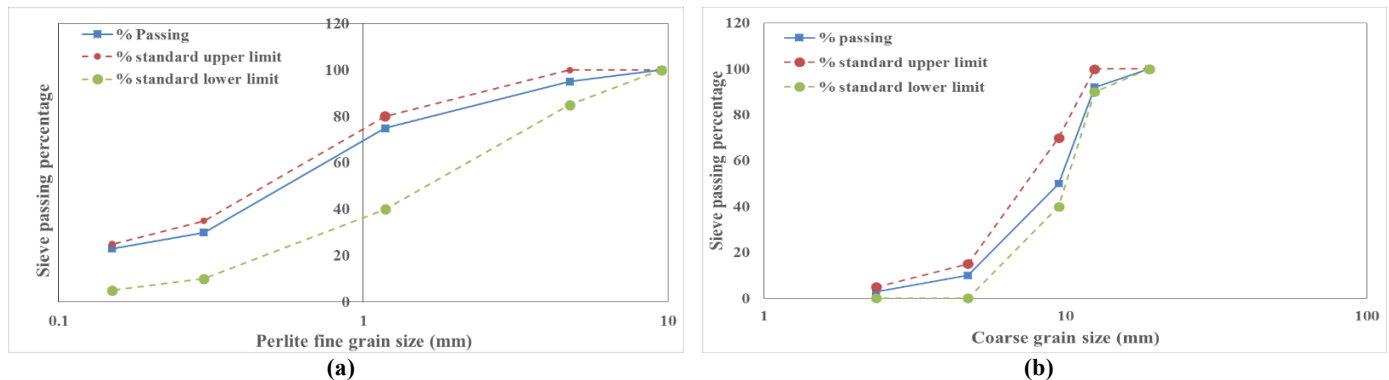


Fig. 1. Modified aggregate gradation curves used in the preparation of lightweight perlite concrete: (a) gradation of perlite fine aggregate; and (b) gradation of coarse aggregate.



Fig. 2. Aggregate separation and incorporation of glass wool fibers.

The selected ranges for glass wool fiber content (0-1.5% by volume) and fiber length (5-50 mm) were determined based on preliminary experiments and previous studies to cover practical ranges for structural lightweight concrete while preventing fiber agglomeration during mixing [30, 31]. The fiber length of 0.17 cm was initially considered in the experimental design; however, it was excluded from the final design space due to its statistically insignificant effect in the ANOVA analysis and its negligible influence on the mechanical responses. Microsilica was incorporated at replacement levels of 7.5%, 10%, and 12.5% by weight of cement. Glass wool fibers were added at volumetric fractions of 0%, 0.5%, 1%, and 1.5%, with lengths of 5, 27.5, and 50 mm.

To ensure uniform fiber dispersion, dry materials including cement, saturated surface-dry (SSD) perlite, microsilica, aggregate, and fibers were initially mixed for 10 min. Water and superplasticizer were then gradually introduced, and mixing continued for an additional 15 min to prevent fiber balling. Fresh concrete was cast into cylindrical molds with dimensions of 105 mm in diameter and 200 mm in height and compacted in three layers to minimize entrapped air. Specimens were initially cured under moist laboratory conditions for 48 h and subsequently demolded. Thereafter, all specimens were water-cured for 42 days to ensure stabilization of the pozzolanic reaction of microsilica [30, 31]. Before testing, specimen dimensions and weights were measured, and their ends were capped with molten sulfur to provide smooth loading surfaces.

The experimental program was designed independently of the RSM analysis. After completing all laboratory tests, the experimental results were imported into Design-Expert software (Version 13) [32] for regression modeling, statistical analysis (ANOVA), response surface generation, and multi-objective optimization.

Although slump was not quantitatively measured in this study, the workability of all mixtures was visually monitored during mixing and casting. Increasing the glass wool fiber content tended to reduce workability and required careful mixing to maintain uniform fiber dispersion and prevent fiber balling. The use of a superplasticizer and prolonged mixing ensured satisfactory casting quality for all mixtures.

2.3. Compressive strength test

All mechanical tests were performed at the age of 42 days. Compressive strength tests were conducted on cylindrical specimens in accordance with ASTM C39 [28], since cylindrical samples provide more uniform behavior than cubic specimens in lightweight concrete evaluation. Loading was applied using a 50-ton capacity compression testing machine at a constant displacement rate of 0.13 mm/min following ASTM C469 [27], corresponding to an average stress rate of approximately 0.25 MPa/s. The maximum failure load of each specimen was recorded.

Furthermore, two Linear Variable Differential Transformers (LVDTs) were employed to measure axial displacement for stress-strain curve acquisition (Fig. 3).



Fig. 3. Experimental setup for the compressive strength test.

Subsequently, load-displacement data were converted into stress-strain values, and the corresponding stress-strain curves were plotted. For each of the 30 mixture proportions, three replicate cylindrical specimens were prepared and tested. The reported compressive strength, density, and quality index values represent the average of the three measurements. Representative failure patterns of the specimens are illustrated in Fig. 4.



Fig. 4. Representative failure patterns of lightweight perlite concrete specimens under compression.

3. Results and discussion

3.1. Stress-strain test

Among the 30 experimentally prepared concrete mixtures, 14 representative mixtures were selected for stress-strain evaluation. These mixtures were selected to represent the control mixture, mixtures with the highest compressive strength, mixtures exhibiting the highest ductility, and mixtures located near the boundaries of the investigated experimental domain. The selected 14 mixtures were used only for detailed stress-strain analysis, whereas the compressive strength results of all 30 mixtures are presented in Section 3.2. The corresponding stress-strain results are summarized in Table 1. Each value reported in Table 1 represents the average of three identical cylindrical specimens tested under the same loading conditions.

Table 1. Specifications and stress-strain test results of the specimens.

Specimen ID	Glass wool fiber content (%)	Glass wool fiber length (cm)	Microsilica content (%)	42-day compressive strength (MPa)	Strain at maximum stress (mm/mm)
1	0	-	7.5	36.79	0.00198
2	0	-	10	37.21	0.00195
3	0	-	12.5	33.43	0.00192
4	1	0.5	12.5	33.73	0.00229
5	0.5	2.75	10	39.99	0.00211
6	0.5	5	12.5	32.85	0.00218
7	0.5	0.5	7.5	38.88	0.00203
8	0.5	5	10	39.52	0.0022
9	1	5	10	39.51	0.00248
10	1	0.5	7.5	36.19	0.00236
11	1	2.75	12.5	33.52	0.00233
12	1.5	0.5	12.5	30.89	0.00256
13	1.5	2.75	10	38.00	0.00271
14	1.5	5	7.5	34.33	0.00287

The experimental results indicate that the stress-strain response of lightweight concrete is governed by the combined influence of microsilica dosage, glass wool fiber content, and fiber length. While microsilica primarily affected the peak stress and elastic response through matrix densification, glass wool fibers mainly influenced the post-peak deformation behavior by delaying crack propagation and increasing strain capacity. The following sections discuss the contribution of each parameter separately.

3.1.1. *Effect of microsilica content*

Increasing the microsilica content from 7.5% to 10% enhanced the compressive strength of lightweight concrete from approximately 36.8 to 37.2 MPa, indicating a moderate yet beneficial improvement in mechanical performance. This enhancement can mainly be attributed to the filler effect of microsilica particles, reduction in pore volume, and strengthening of the interfacial transition zone (ITZ) due to the pozzolanic reaction. However, further increasing the microsilica content to 12.5% resulted in excessive matrix densification and reduced stress redistribution capability within the cement paste. Consequently, the increase in compressive strength was no longer proportional to the increase in microsilica content, while the strain at peak stress tended to decrease, indicating a transition toward a relatively more brittle mechanical response. These observations are consistent with previous studies [33–37], which reported that microsilica replacement levels of approximately 8–10% generally provide the optimum balance between matrix densification and mechanical performance. Beyond this range, the increased specific surface area raises water demand and may reduce particle dispersion efficiency, resulting in only marginal or even negative improvements in mechanical properties.

3.1.2. *Effect of glass wool fiber content*

Increasing the glass wool fiber content led to higher ultimate strain values and improved ductility of lightweight concrete. Compared with the control mixture, specimens containing 1.5% glass wool fibers exhibited an approximately 45% increase in peak strain, confirming the substantial contribution of fibers to deformation capacity. The fibers acted as crack-bridging elements, absorbing part of the stress concentration energy and delaying rapid crack propagation. As a result, the concrete retained part of its load-carrying capacity after crack initiation and exhibited a more ductile response. This behavior is mainly associated with stress transfer through the fibers and improved stress distribution within the cementitious matrix. According to recent studies [38–43], incorporating Glass wool fibers within an optimum volumetric range of approximately 1–1.5% can significantly improve ultimate strain, energy absorption capacity, and ductility of lightweight concrete. Nevertheless, excessive fiber content, particularly beyond 1.5%, may lead to fiber agglomeration, reduced workability, weaker bonding, and formation of weak zones within the matrix. The present experimental results demonstrated that a fiber content of 1.5% produced the highest deformation capacity among the investigated mixtures. However, compressive strength did not increase proportionally because excessive fiber content tends to reduce workability and matrix uniformity. Therefore, the optimum fiber dosage depends on the selected performance criterion.

3.1.3. *Effect of glass wool fiber length*

Experimental observations indicated that increasing the glass wool fiber length from 5 to 50 mm enhanced the ultimate strain and energy absorption capacity of lightweight concrete. Longer fibers, especially 50 mm fibers, provided more effective mechanical interlocking with the cementitious matrix and improved crack-bridging action, thereby preventing sudden crack propagation and producing a smoother post-peak response. Through stress transfer along crack paths, the fibers redistributed stresses and enhanced the ductility of the concrete. In contrast, shorter fibers were mainly effective in controlling initial microcracks but had a more limited influence on the overall post-cracking behavior. Previous investigations [44–47] have also reported that increasing fiber length improves fiber-matrix bonding, fracture strain, and energy absorption capacity in lightweight and high-performance concretes, although excessively long fibers may lead to non-uniform distribution and localized fiber clustering. Although fiber length was treated as a numerical factor in the RSM analysis, the experimental program included only three discrete fiber lengths (0.5, 2.75, and 5 cm). Therefore, intermediate values predicted by the response surface model should be interpreted as mathematical interpolations within the investigated domain rather than experimentally validated optima. Additional experimental verification using intermediate fiber lengths is recommended in future studies to further assess the robustness and generalizability of the proposed model.

It should be emphasized that the 50 mm fibers exhibited the highest ultimate strain and energy absorption capacity, whereas the maximum quality index (R/ρ) was achieved with the 5 mm fibers. Accordingly, the optimum fiber length is response-dependent, and no single fiber length can be regarded as universally optimal for all mechanical performance indicators. Longer fibers are preferable for improving post-peak behavior and energy absorption, whereas shorter fibers provide higher strength-to-density efficiency when the quality index is adopted as the optimization criterion.

3.1.4. *Elastic modulus and energy absorption*

Fig. 5 presents representative stress-strain curves of lightweight concrete containing different glass wool fiber volume fractions (0–1.5%). The curves illustrate the influence of fiber reinforcement on both the pre-peak elastic response and the post-peak deformation behavior.

In the control mixtures (Mixes 1–3), which contain no glass wool fibers, the stress-strain curves exhibit a steep descending branch immediately after the peak stress, indicating limited post-peak deformation capacity and a relatively brittle mechanical response. In contrast, with increasing fiber content, the descending branch of the curve becomes more gradual, reflecting a more ductile and

progressive failure response. For example, the ultimate strain increased from approximately 0.00192–0.00198 in the control mixtures to 0.00271–0.00287 in the mixtures containing 1.5% glass wool fibers, corresponding to an increase of approximately 40–50%. This improvement demonstrates the effectiveness of glass wool fibers in enhancing the deformation capacity of lightweight concrete through crack-bridging and stress redistribution mechanisms. These observations indicate that the incorporation of microsilica and glass wool fibers significantly improves the post-peak deformation behavior of the investigated lightweight concrete mixtures. However, the applicability of these mixtures to specific structural members should be evaluated considering the design requirements and loading conditions of the intended application.

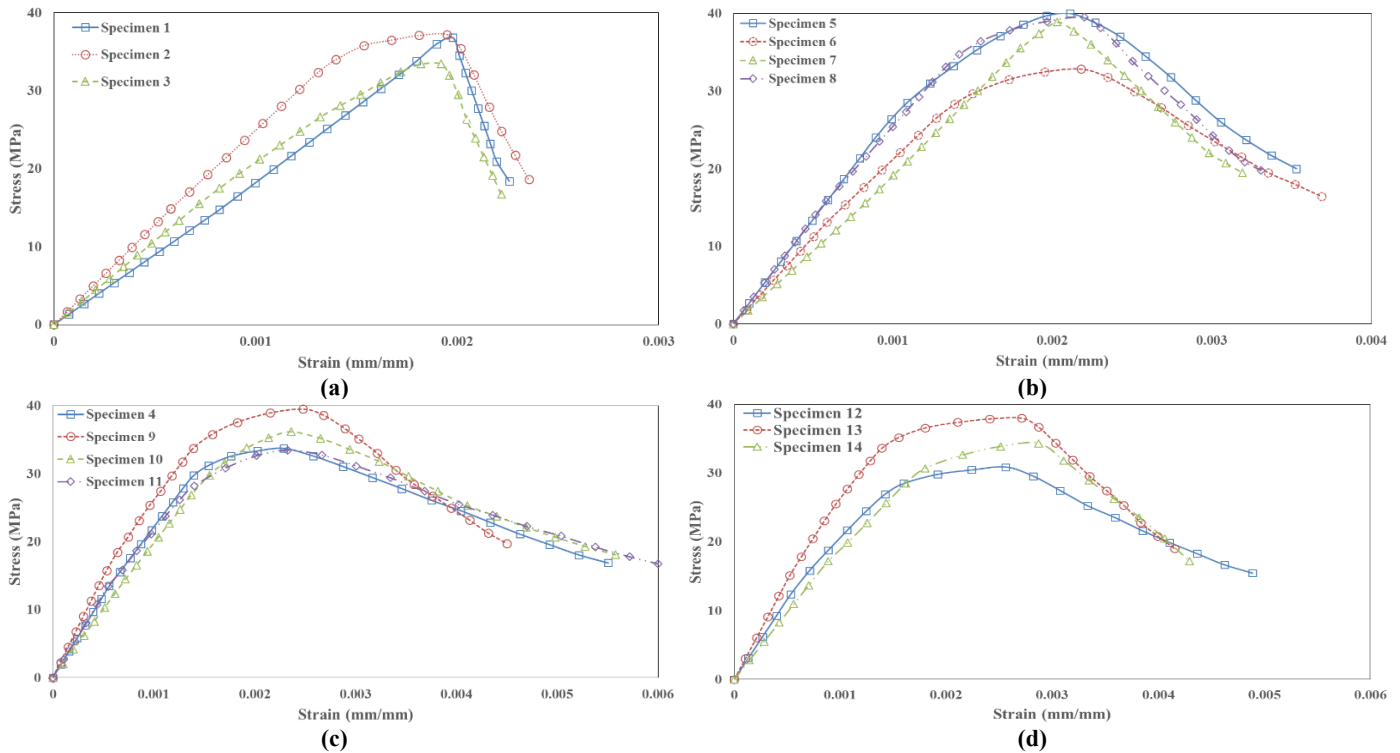


Fig. 5. Stress-strain behavior of lightweight perlite concrete containing different glass wool fiber contents: (a) control mixture without glass wool fibers; (b) mixture containing 0.5% glass wool fibers; (c) mixture containing 1.0% glass wool fibers; and (d) mixture containing 1.5% glass wool fibers.

For a fair comparison of energy absorption capacity among mixtures with different ultimate strains, the absorbed energy was calculated as the area under the stress-strain curve up to 50% of the peak stress. This approach, widely adopted in similar studies, enables consistent comparison of post-peak behavior. Based on the results presented in Table 2, the absorbed energy increased from approximately 60–78 kJ/m³ in the control mixtures to values as high as 194 kJ/m³ in the fiber-reinforced mixtures, representing an improvement of more than 150% under the investigated conditions.

Table 2. Modulus of elasticity and absorbed energy of the specimens.

Specimen ID	Modulus of elasticity (GPa)	Energy absorption up to 50% of peak stress (kJ/m ³)
1	17.91	64.63
2	25.64	77.55
3	21.52	60.63
4	24.12	178.93
5	26.93	129.27
6	22.36	113.18
7	18.79	104.73
8	27.18	121.13
9	29.73	170.53
10	20.08	188.10
11	24.58	194.13
12	23.22	145.91
13	28.89	154.37
14	19.49	137.87

The elastic modulus of each mix was determined according to ASTM C469-02 [27] using Eq. 1:

$$E = \frac{\sigma_2 - \sigma_1}{\varepsilon_2 - \varepsilon_1} \quad (1)$$

where σ_1 is the stress corresponding to a strain value of 0.00005, σ_2 is the stress corresponding to 0.4 ultimate strength, ε_1 is equal to 0.00005, and ε_2 are the strains corresponding to the stress σ_2 .

The results presented in Table 2 indicate that the elastic modulus and energy absorption capacity do not necessarily follow identical trends. While the elastic modulus mainly reflects the stiffness of the cementitious matrix before cracking, the absorbed energy is governed predominantly by the post-peak crack propagation process and the ability of glass wool fibers to bridge developing cracks. Consequently, mixtures with comparable elastic modulus values may exhibit substantially different energy absorption capacities. In this study, the effects of glass wool fiber content and length, as well as microsilica content, on the elastic modulus and energy absorption capacity of lightweight concrete were investigated. The results indicated that incorporating approximately 1% glass wool fibers produced the highest elastic modulus (29.73 GPa), consistent with previous studies [48], whereas the highest absorbed energy (194.13 kJ/m³) was obtained for another mixture containing the same fiber dosage but different microsilica content and fiber length. These findings demonstrate that the optimum mixture depends on the selected mechanical performance indicator rather than on a single response parameter. Increasing the fiber content to 1.5% resulted in a slight reduction in performance due to fiber agglomeration and reduced matrix homogeneity [49]. The investigation of fiber length revealed that the maximum energy absorption capacity was achieved at a fiber length of 2.75 cm, as this length provides more effective post-cracking reinforcement compared to the initial elastic response stage [50]. Increasing the microsilica content up to 10% enhanced both the elastic modulus and energy absorption, which is attributed to pore refinement, densification of the cement paste, and improved interfacial bonding [51]. However, further increase to 12.5% resulted in a reduction in performance, mainly due to higher water demand, non-uniform particle dispersion, and the formation of additional microcracks. The results also indicated that a direct linear relationship does not always exist between elastic modulus and energy absorption capacity. In some cases, specimens with lower modulus exhibited higher post-peak energy absorption, which is governed by the combined effect of fiber content, fiber length, and microsilica content [52]. Two failure modes were observed: brittle failure characterized by a sudden drop in the stress-strain curve, and ductile failure with a gradual post-peak decline. Overall, the experimental observations confirm that microsilica mainly enhances the stiffness and strength of the cementitious matrix through pore refinement and interfacial transition zone (ITZ) densification, whereas glass wool fibers primarily improve post-peak deformation behavior through crack-bridging mechanisms. The simultaneous incorporation of both materials therefore provides a balanced improvement in stiffness, strength, ductility, and energy absorption, explaining the superior overall mechanical efficiency observed in the optimized mixtures [49].

3.1.5. Microstructural analysis (SEM)

To investigate the influence of microsilica and glass wool fibers on the microstructure of lightweight perlite concrete, selected specimens were examined using scanning electron microscopy (SEM). SEM images at magnifications of 1000× and 3000× are presented in Fig. 6.

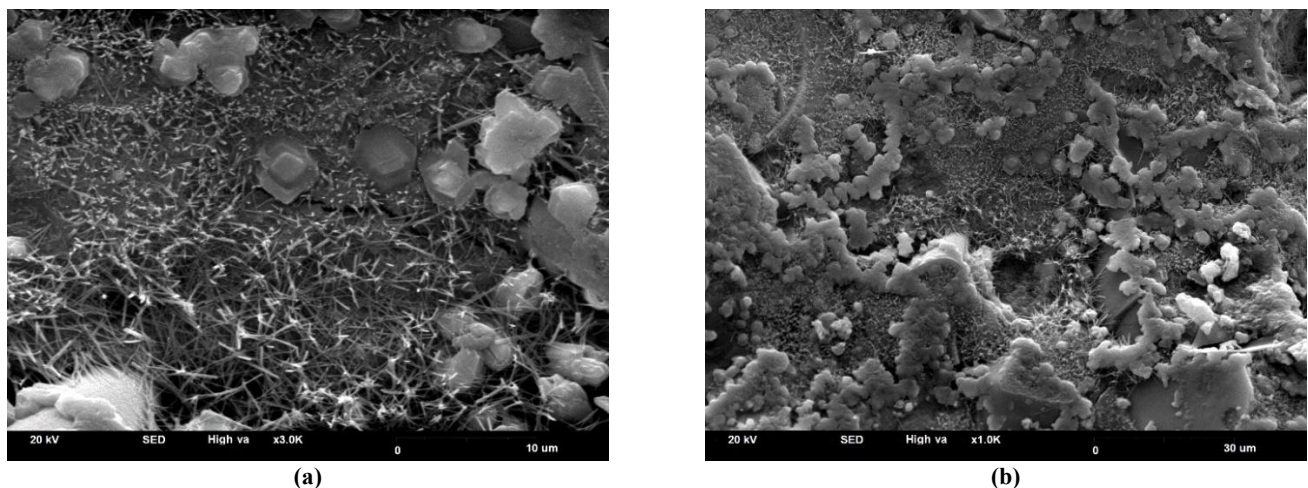


Fig. 6. SEM micrographs of lightweight perlite concrete containing microsilica and glass wool fibers: (a) microstructure at 1000× magnification; and (b) microstructure at 3000× magnification, illustrating the densified cementitious matrix and fiber-matrix interaction.

The microstructural observations revealed that the incorporation of microsilica contributed to matrix densification and a relative reduction in porosity within the lightweight concrete structure. The observed matrix densification can be attributed to the pozzolanic reaction between microsilica and calcium hydroxide released during cement hydration, producing additional calcium silicate hydrate (C-S-H) gel. This secondary hydration product refines the pore structure, strengthens the interfacial transition zone (ITZ), and contributes to the improvement in compressive strength observed in the experimental results. Due to its ultrafine particles and pozzolanic activity, microsilica filled microvoids and improved the uniformity and compactness of the cementitious matrix. In several regions, hydration products with needle-like and network-shaped morphologies were observed, indicating the formation of hydrated phases and improvement of the interfacial transition zone (ITZ) between the cement paste and aggregates. Higher magnification images further demonstrated that the glass wool fibers were well embedded within the cementitious matrix and acted as bridging elements across microcracks in some regions. The effective mechanical anchorage of the fibers within the cementitious matrix enabled efficient crack-bridging during loading, thereby delaying crack opening and reducing stress concentration at the crack tip. This mechanism explains the experimentally observed increase in ductility and post-peak energy absorption. Moreover,

the relatively good adhesion between the fibers and the surrounding matrix suggests an effective fiber-matrix interaction. The SEM observations confirm that the simultaneous incorporation of microsilica and glass wool fibers improved both matrix densification and crack-control mechanisms, leading to enhanced mechanical performance of lightweight perlite concrete. These findings are in good agreement with the compressive strength results, stress-strain behavior, and quality index analysis.

3.2. Compressive strength test

Compressive strength was experimentally determined for all 30 concrete mixtures after 42 days of water curing. For each mixture, three cylindrical specimens were tested under identical loading conditions, and the average compressive strength was used for subsequent statistical analysis and RSM modeling.

To evaluate the mechanical efficiency of lightweight concrete, a quality index (R/ρ) was adopted. This parameter is defined as the ratio of the 42-day compressive strength (R_{42} , MPa) to the concrete density (ρ , kg/m³). Although not dimensionless, this index provides a practical measure of strength achieved per unit density and is therefore useful for comparing structural lightweight concretes with different densities. Higher R/ρ values indicate greater mechanical efficiency. In this study, the quality index of lightweight concrete was defined as Eq. 2.

$$\text{Quality index} = \left(\frac{R_{42}}{\rho} \right) \times 100 \quad (2)$$

where R_{42} is the 42-day compressive strength and ρ is the concrete density. Unlike compressive strength, which evaluates only the load-bearing capacity, the quality index simultaneously considers strength and self-weight. Therefore, mixtures with the highest compressive strength do not necessarily exhibit the highest quality index. The complete experimental matrix together with the measured density, compressive strength, and calculated quality index of all 30 mixtures is presented in Table 3. All values correspond to experimentally measured data rather than RSM predictions.

Table 3. Specimen details and compressive strength test results.

Specimen ID	Glass wool fiber content (%)	Glass wool fiber length (cm)	Microsilica content (%)	42-day compressive strength (MPa)	Density (kg/m ³)	Quality index
1	0	-	7.5	36.79	1848	1.99
2	0	-	10	37.21	1842	2.02
3	0	-	12.5	33.43	1839	1.82
4	0.5	0.5	7.5	38.88	1829	2.13
5	0.5	0.5	10	39.91	1825	2.19
6	0.5	0.5	12.5	33.74	1820	1.85
7	0.5	2.75	7.5	36.49	1821	2.00
8	0.5	2.75	10	39.99	1818	2.20
9	0.5	2.75	12.5	33.38	1815	1.84
10	0.5	5	7.5	36.16	1807	2.00
11	0.5	5	10	39.52	1806	2.19
12	0.5	5	12.5	32.85	1800	1.83
13	1	0.5	7.5	36.19	1794	2.02
14	1	0.5	10	39.87	1787	2.23
15	1	0.5	12.5	33.73	1765	1.91
16	1	2.75	7.5	36.03	1789	2.01
17	1	2.75	10	39.65	1781	2.23
18	1	2.75	12.5	33.50	1763	1.90
19	1	5	7.5	35.76	1781	2.01
20	1	5	10	39.51	1779	2.22
21	1	5	12.5	31.70	1760	1.80
22	1.5	0.5	7.5	34.83	1751	1.99
23	1.5	0.5	10	38.22	1739	2.20
24	1.5	0.5	12.5	30.89	1724	1.79
25	1.5	2.75	7.5	35.18	1747	2.01
26	1.5	2.75	10	38.00	1733	2.19
27	1.5	2.75	12.5	30.19	1720	1.75
28	1.5	5	7.5	34.33	1740	1.97
29	1.5	5	10	37.79	1728	2.19
30	1.5	5	12.5	29.65	1718	1.73

The experimental results indicate that the highest compressive strength (40.0 MPa) was obtained for the mixture containing 10% microsilica, 0.5% glass wool fibers, and a fiber length of 27.5 mm. However, this mixture did not provide the highest quality index because its density was higher than that of several other mixtures. Consequently, the optimum mixture depends on the selected optimization criterion. Fig. 7 summarizes the experimentally measured variation of the quality index with respect to glass wool fiber dosage, microsilica content, and fiber length. These plots are presented solely to illustrate the experimental trends before statistical modeling.

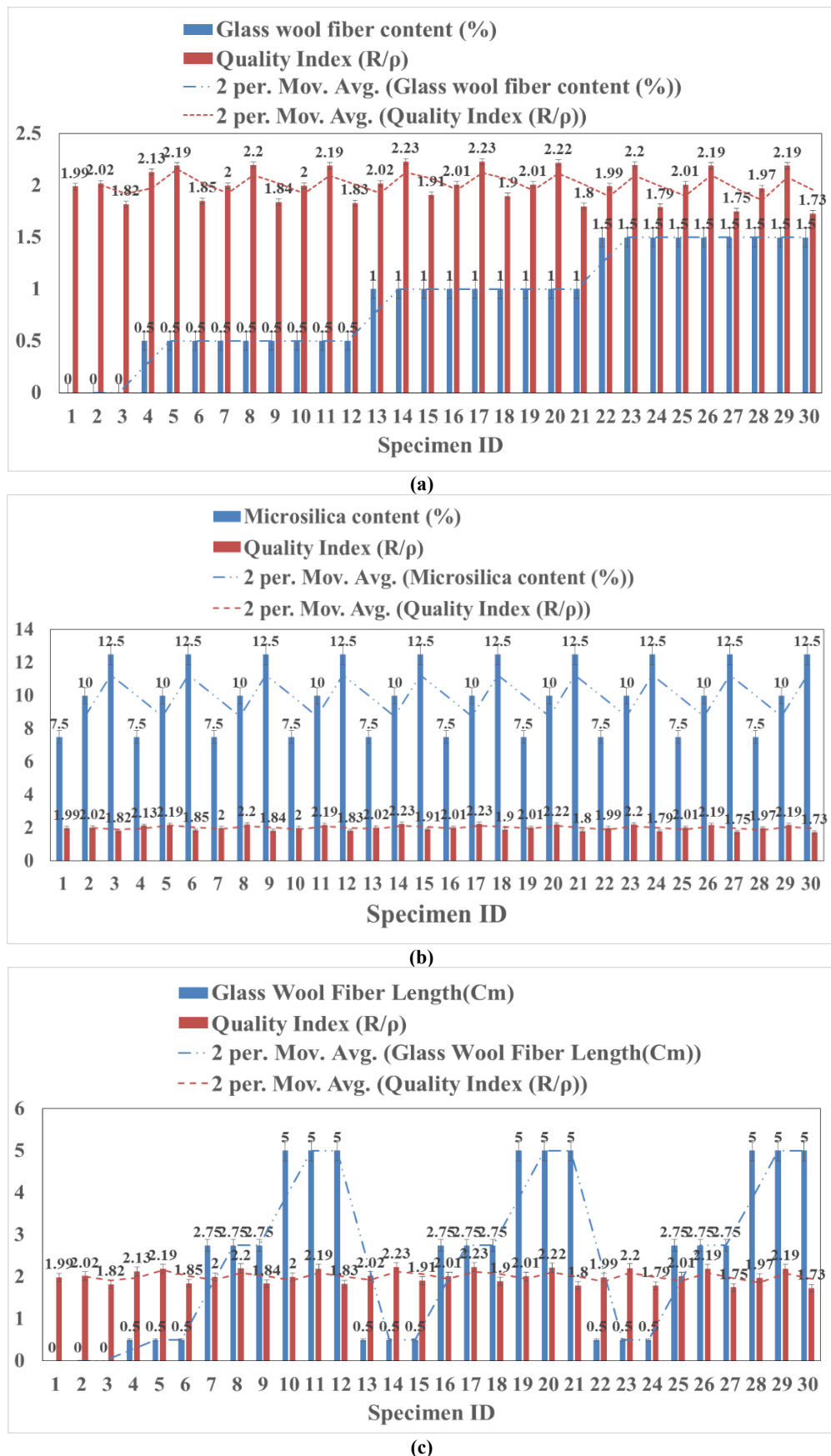


Fig. 7. Effects of the investigated variables on the quality index (R/ρ): (a) influence of glass wool fiber content; (b) influence of microsilica content; and (c) influence of glass wool fiber length.

Following the experimental investigation, the measured responses were imported into Design-Expert® (Version 13) [32] for statistical evaluation using Response Surface Methodology (RSM). The software was employed only for regression analysis and multi-objective optimization of the experimentally obtained results. To assess the effects of individual factors and their interactions on the response, analysis of variance (ANOVA) and regression modeling were employed. These methods enable the identification of statistically significant relationships between the input variables and the quality index.

3.2.1. Software data analysis

The experimentally measured quality index values listed in Table 3 were analyzed using Design-Expert® software (Version 13) [32]. Glass wool fiber content (factor A), microsilica content (factor B), and fiber length (factor C) were treated as independent variables, whereas the quality index (R/ρ) was considered the response variable.

In the box plots (Fig. 8), the median line and the first and third quartiles (25–75%) represent the distribution of the response data. The results indicated that increasing fiber content up to 1% improves the quality index, while further increases lead to a reduction in performance. Similarly, microsilica content up to 10% enhances the quality index, whereas a decrease is observed at 12.5%. For fiber length, the highest quality index was obtained at 0.5 cm, followed by a decreasing trend.

Accordingly, the combination of 10% microsilica, 1% glass wool fibers, and 0.5 cm fiber length was identified as an optimal region for maximizing the quality index. It should be noted that this optimum region was identified from the experimental observations only. The continuous optimum predicted by the response surface model is presented later in Section 3.2.6.

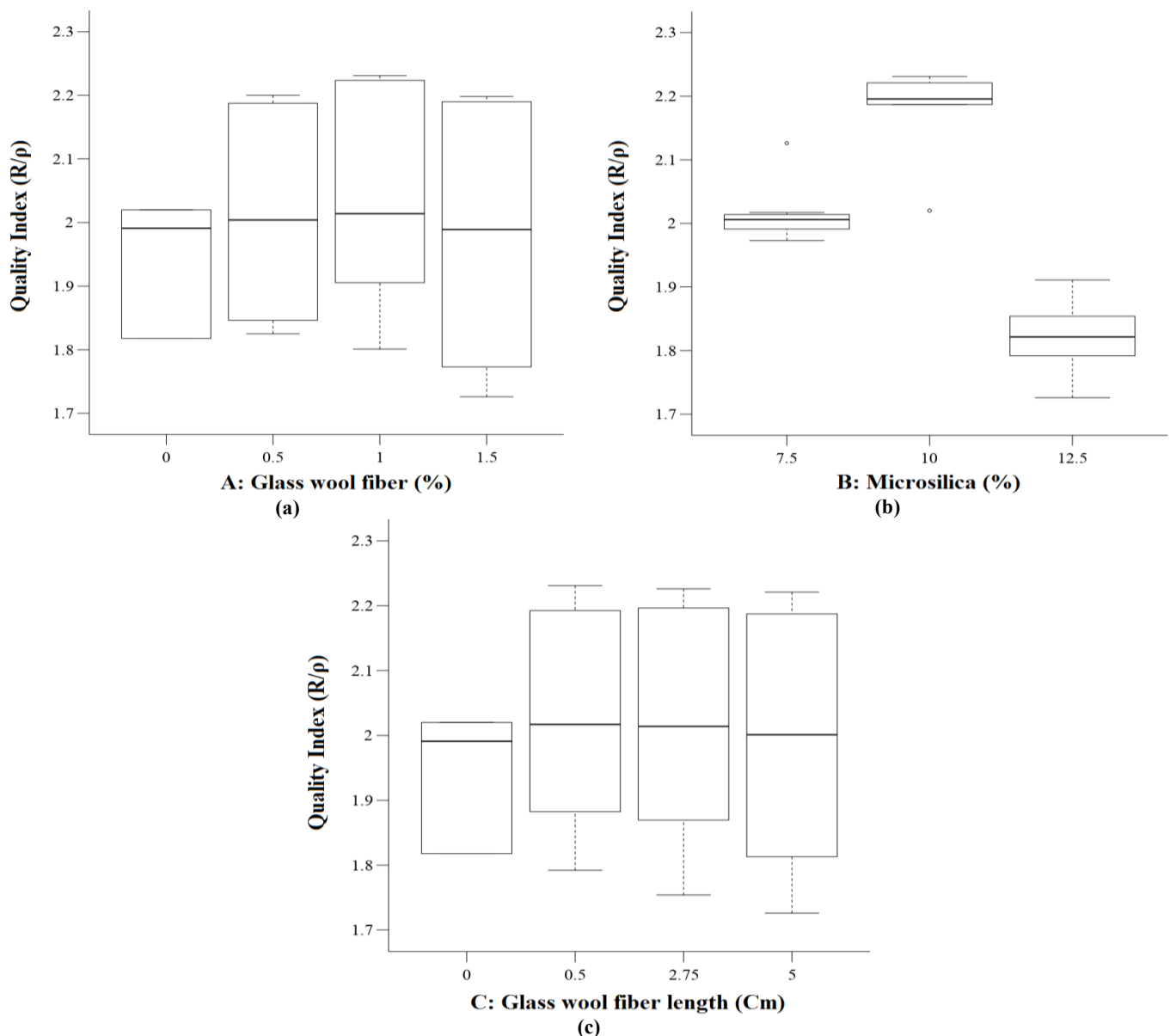


Fig. 8. Boxplots illustrating the distribution of the Quality Index (R/ρ) with respect to the investigated variables: (a) glass wool fiber content; (b) microsilica content; and (c) glass wool fiber length.

3.2.2. Analysis of the quality index data

Several regression models, including linear, two-factor interaction (2FI), quadratic, and cubic models, were evaluated using Design-Expert® (Version 13) [32], and the most appropriate model was selected according to the statistical criteria summarized in

Table 4. The experimental data were analyzed using Response Surface Methodology (RSM) implemented in Design-Expert® (Version 13) [32]. Three independent variables were considered, namely glass wool fiber content (factor A), microsilica content (factor B), and glass wool fiber length (factor C), while the quality index (R/ρ) was selected as the response variable. Linear, two-factor interaction (2FI), quadratic, and cubic polynomial models were evaluated. The final model was selected according to the sequential model sum of squares, model significance, adjusted coefficient of determination (Adjusted R^2), predicted coefficient of determination (Predicted R^2), and model hierarchy.

Table 4. Model selection summary for response surface model selection.

Sequential model sum of squares [type I]					
Source	Sum of squares	df	Mean square	F-value	P-value
Mean vs total	120.83	1	120.83		
Linear vs mean	0.1847	3	0.0616	2.89	0.0547
2FI vs linear	0.0107	3	0.0036	0.1511	0.9279
Quadratic vs 2FI	0.5025	3	0.1675	81.71	< 0.0001
Cubic vs quadratic	0.0269	8	0.0034	2.86	0.0495
Residual	0.0141	12	0.0012		
Total	121.57	30	4.05		
Model summary statistics					
Source	Std. Dev.	R^2	Adjusted R^2	Predicted R^2	PRESS
Linear	0.1460	0.2499	0.1634	0.0309	0.7161
2FI	0.1537	0.2644	0.0725	-0.2477	0.9219
Quadratic	0.0453	0.9445	0.9195	0.8612	0.1026
Cubic	0.0343	0.9809	0.9538	0.8377	0.1199
Fit summary					
Source	Model p-value	Adjusted R^2	Predicted R^2		
Design model	< 0.0001	0.9231	0.8659	Recommended	
Linear	0.0547	0.1634	0.0309		
2FI	0.9279	0.0725	-0.2477		
Quadratic	< 0.0001	0.9195	0.8612	Suggested	
Cubic	0.0495	0.9538	0.8377	Aliased	

Among the evaluated regression models, the quadratic model was selected because it provided the best compromise between prediction accuracy and model simplicity. As shown in Table 4, the quadratic model exhibited a statistically significant p-value (< 0.0001), together with high Adjusted R^2 (0.9195) and Predicted R^2 (0.8612) values, indicating excellent agreement between experimental observations and model predictions. Although the cubic model exhibited a slightly higher coefficient of determination, it was aliased because the available experimental data were insufficient to estimate all higher-order coefficients independently. Therefore, the quadratic model was selected as the most statistically reliable regression model.

After selecting the quadratic model, an analysis of variance (ANOVA) was performed to identify the statistically significant factors affecting the quality index. The significance of each main effect, interaction term, and quadratic term was evaluated at a confidence level of 95% ($p < 0.05$). The ANOVA results of the reduced model are presented in Table 5.

Table 5. Analysis of variance (ANOVA) for the reduced quadratic response surface model.

Source	Sum of squares	df	Mean square	F-value	P-value	Remark
Model	0.6978	8	0.0872	44.53	< 0.0001	Significant
A (glass wool fiber content)	0.0062	1	0.0062	3.18	0.0890	Not significant
B (microsilica content)	0.1606	1	0.1606	82.01	< 0.0001	Significant
C (glass wool fiber length)	0.0066	1	0.0066	3.39	0.0798	Not significant
A × B	0.0006	1	0.0006	0.3152	0.5804	Not significant
A × C	0.0001	1	0.0001	0.0382	0.8469	Not significant
B × C	0.0002	1	0.0002	0.0875	0.7702	Not significant
A ²	0.0262	1	0.0262	13.40	0.0015	Significant
B ²	0.4762	1	0.4762	243.09	< 0.0001	Significant
Residual	0.0411	21	0.0020			
Cor total	0.7389	29				

Note: Factor coding is coded. Sum of squares is type III (partial).

Model statistics			
Statistic	Value	Statistic	Value
Std. Dev.	0.0443	R ²	0.9443
Mean	2.01	Adjusted R ²	0.9231
C.V. %	2.21	Predicted R ²	0.8659
		Adeq precision	19.5336

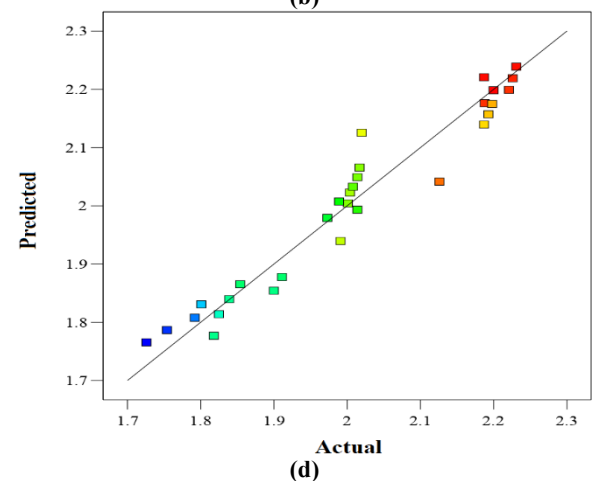
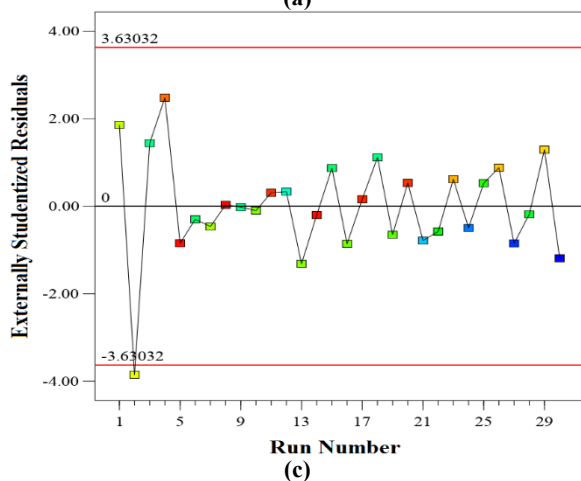
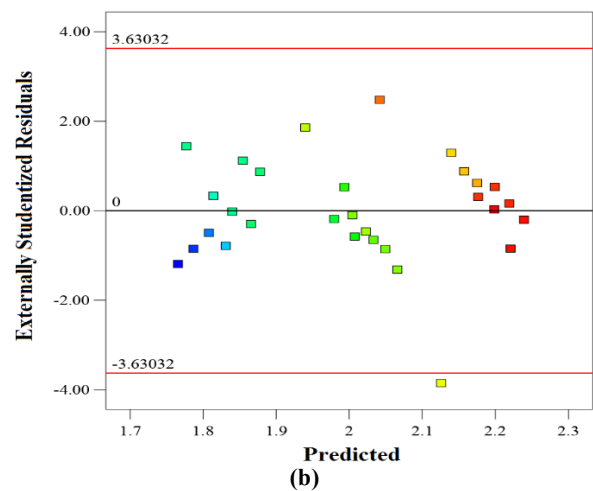
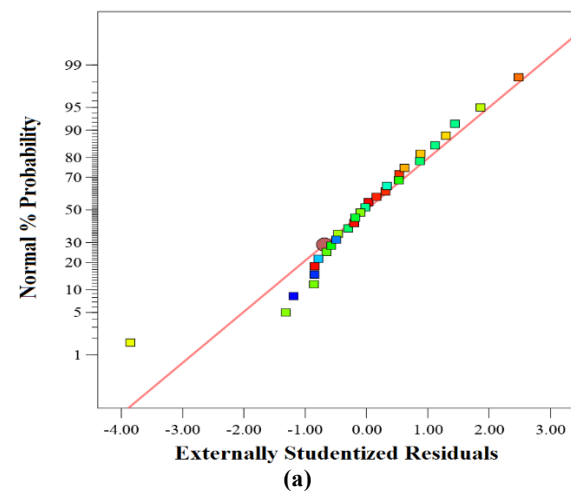
The ANOVA results indicate that microsilica content (factor B) was the most influential variable affecting the quality index ($p < 0.0001$), whereas the linear effects of glass wool fiber content (factor A) and fiber length (factor C) were not statistically significant within the investigated experimental range ($p > 0.05$). Nevertheless, the quadratic effects of fiber content (A^2) and microsilica content (B^2) were statistically significant, confirming the existence of optimum values rather than purely linear relationships. The absence of statistically significant interaction terms (AB, AC, and BC) indicates that the effects of the investigated variables were predominantly independent within the studied design space. Consequently, the overall response was governed mainly by the individual contribution of microsilica content together with the nonlinear behavior of microsilica and glass wool fiber dosage. This finding suggests that the influence of fiber length is more pronounced in post-peak behavior and strain-related responses than in the strength-to-density ratio (R/ρ).

High values of R^2 and Predicted R^2 confirm good model fitting and reliable prediction of new observations. Furthermore, a high Adequate Precision value indicates an adequate signal-to-noise ratio and confirms the suitability of the model for mixture design applications. Overall, the statistical analysis confirms the robustness of the model and supports its application in engineering practice.

The final regression equation expressed in terms of actual factor values is presented below and can be used to predict the quality index within the investigated experimental domain only. Extrapolation beyond the investigated ranges is not recommended.

$$\text{Quality index} = -1.82487 + 0.329672(A) + 0.822649(B) - 0.004593(C) - 0.004701(AB) + 0.002029(AC) - 0.000629(BC) - 0.164751(A^2) - 0.042760(B^2) \quad (3)$$

The regression equation demonstrates that microsilica content has the strongest positive contribution to the quality index, whereas the significant quadratic coefficients indicate the presence of optimum material proportions. Consequently, increasing microsilica or fiber dosage beyond their optimum levels does not continuously improve the response, which agrees well with the experimental observations.



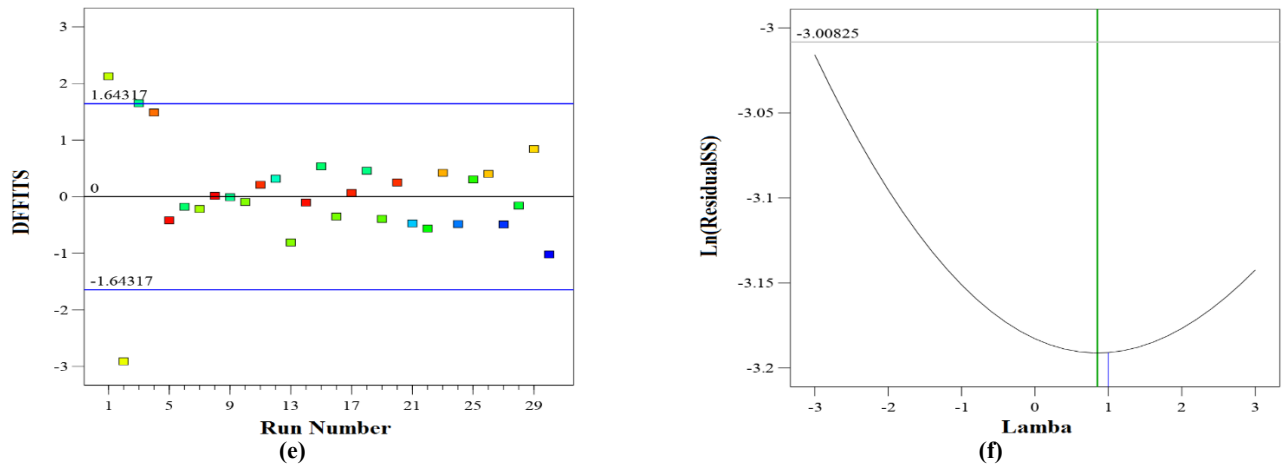


Fig. 9. Diagnostic plots used for validation of the quadratic response surface model: (a) normal probability plot of residuals; (b) residuals versus predicted values; (c) residuals versus run order; (d) predicted versus actual values; (e) DFFITS versus run order; and (f) Box-Cox plot for power transformation.

The diagnostic plots presented in Fig. 9 confirm the adequacy of the selected quadratic model. The normal probability plot indicates that the residuals are approximately normally distributed, while the residual-versus-predicted plot demonstrates a random distribution without systematic trends, confirming the absence of significant heteroscedasticity. Furthermore, the Box-Cox analysis indicates that no transformation of the response variable is required because the confidence interval includes $\lambda = 1$. These diagnostic results demonstrate that the assumptions required for regression analysis were satisfactorily fulfilled and therefore support the reliability of the developed RSM model.

Fig. 10 illustrates the main effects of glass wool fiber content (A), microsilica content (B), and glass wool fiber length (C) on the quality index (R/ρ). The response surface model indicates that microsilica content and glass wool fiber dosage exhibit nonlinear relationships with the quality index, resulting in distinct optimum values of approximately 9.39% and 0.87%, respectively. In contrast, fiber length showed a comparatively smaller influence on the quality index within the investigated range. These trends are consistent with the ANOVA results, which identified the quadratic effects of microsilica content and fiber dosage as statistically significant. It should be emphasized that the optimum values shown in Fig. 10 are mathematical predictions obtained from the continuous RSM model and should not be interpreted as experimentally tested mixtures. They represent interpolated optimum conditions within the investigated design space.

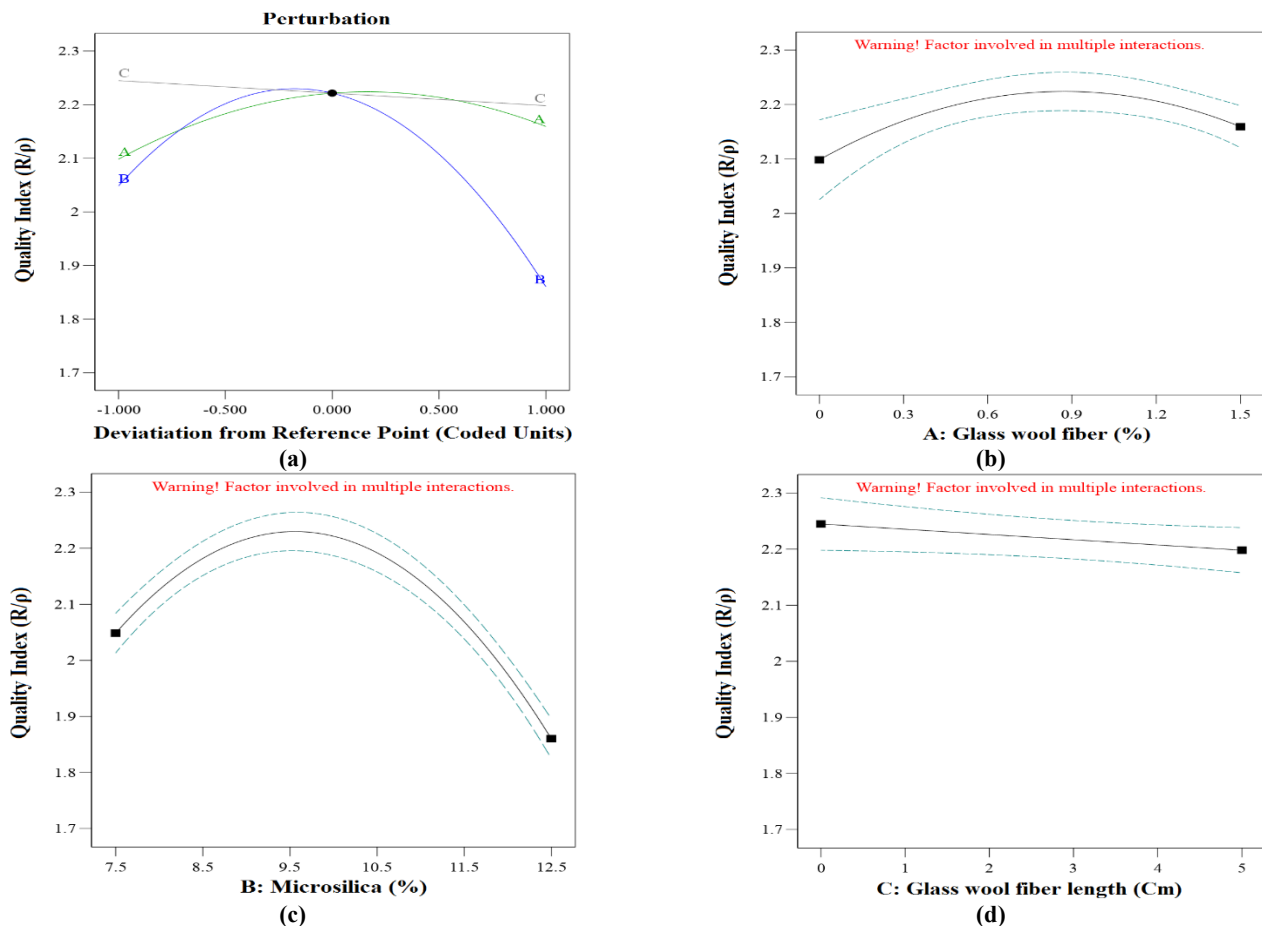


Fig. 10. Main effect plots showing the influence of the investigated variables on the quality index (R/ρ): (a) combined effects of all factors; (b) glass wool fiber content; (c) microsilica content; and (d) glass wool fiber length.

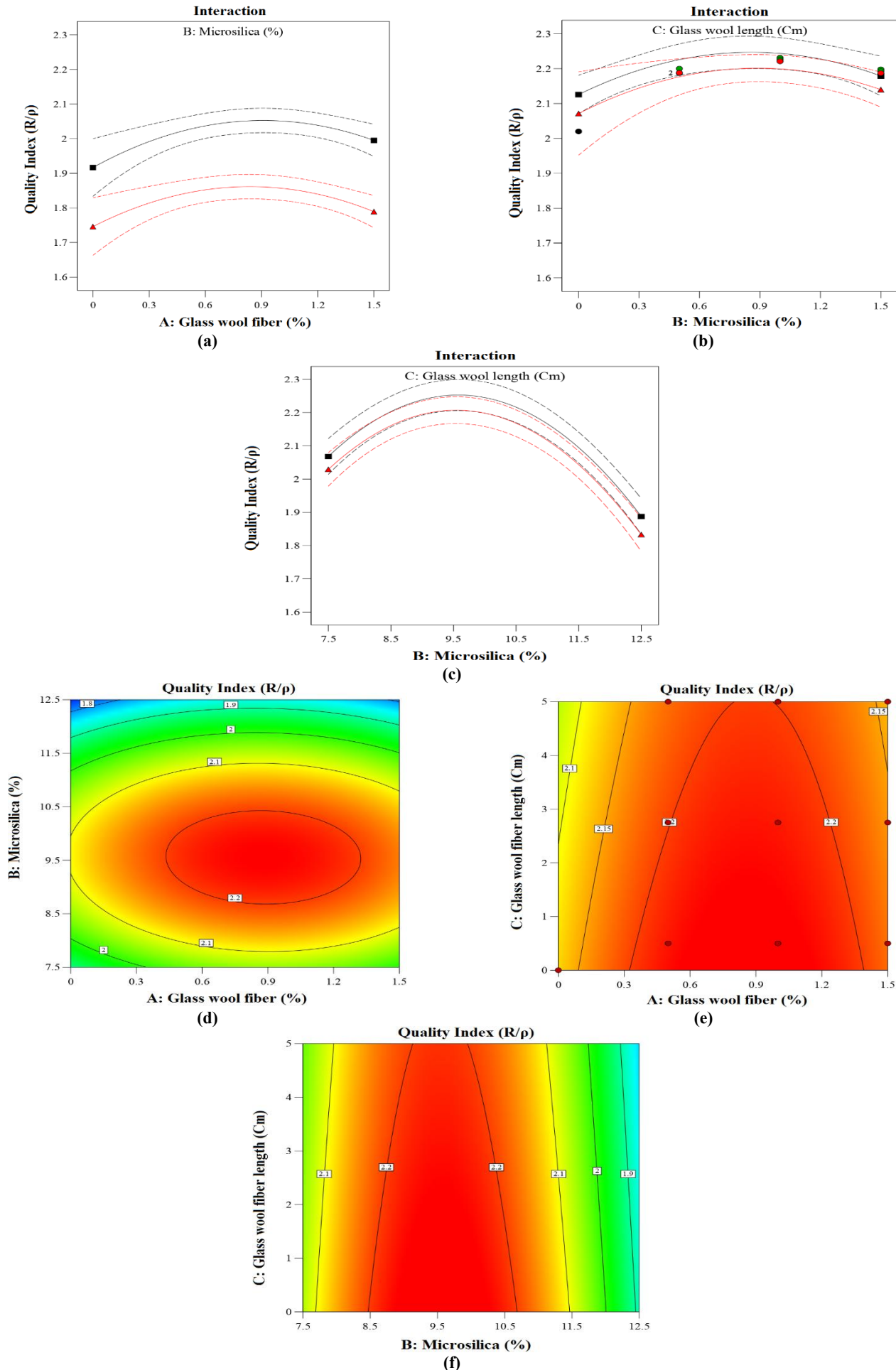


Fig. 11. Interaction and contour plots illustrating the effects of the investigated variables on the Quality Index (R/ρ): (a) interaction plot of factors A and B; (b) interaction plot of factors A and C; (c) interaction plot of factors B and C; (d) contour plot of factors A and B; (e) contour plot of factors A and C; and (f) contour plot of factors B and C.

Fig. 11 presents the contour plots describing the interaction between the investigated variables and the predicted quality index. Although the interaction terms were not statistically significant according to the ANOVA results, the contour plots provide a useful graphical representation of the response surface and facilitate visualization of the optimum design region. The red circles indicate the experimentally tested mixtures, whereas the continuous contours represent the response predicted by the RSM model.

Fig. 12 illustrates the three-dimensional response surfaces generated by the quadratic regression model. The surfaces predict the variation of the quality index throughout the investigated experimental domain. Therefore, the predicted optimum points should be interpreted as model estimations rather than direct experimental observations.

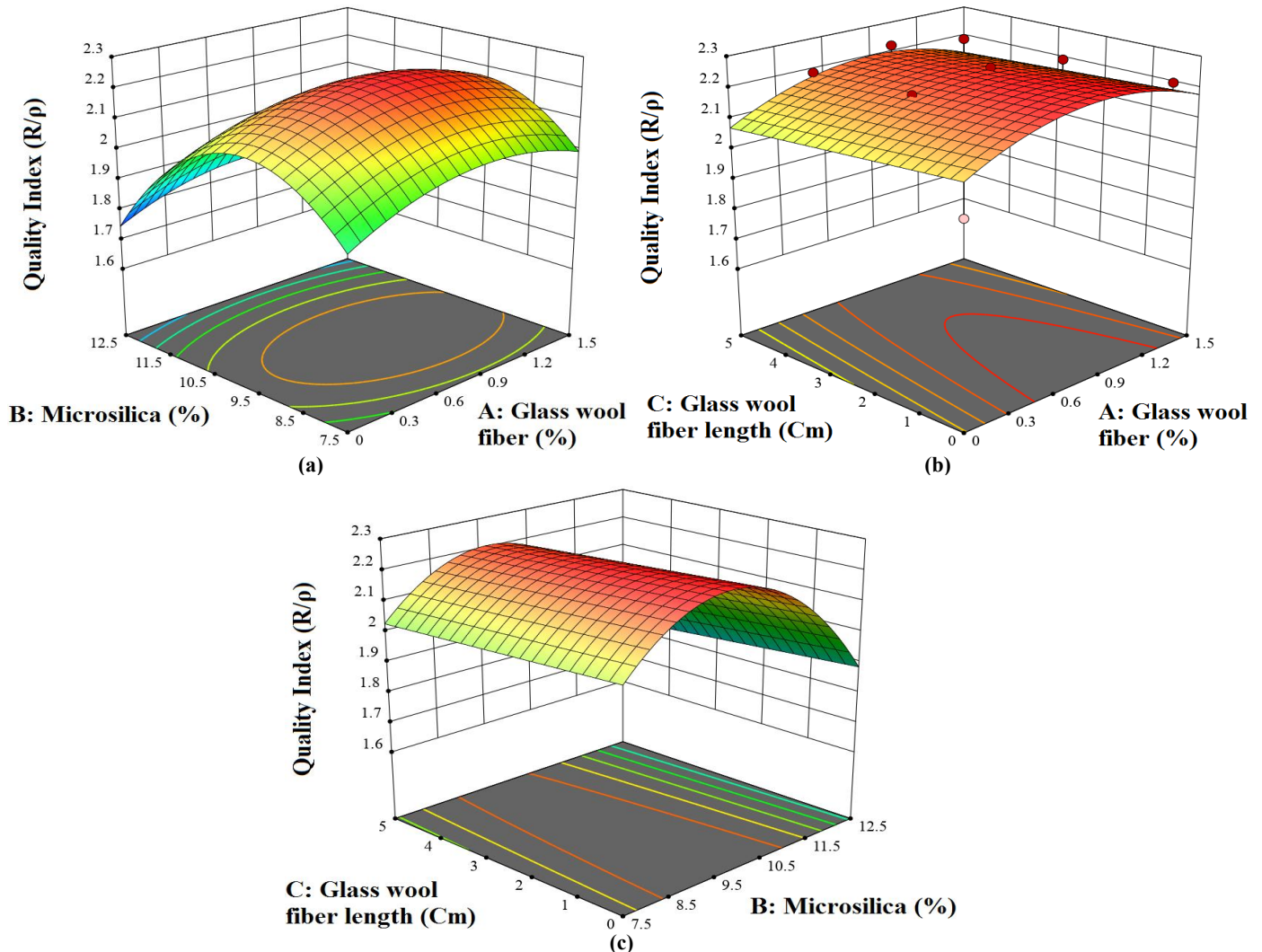
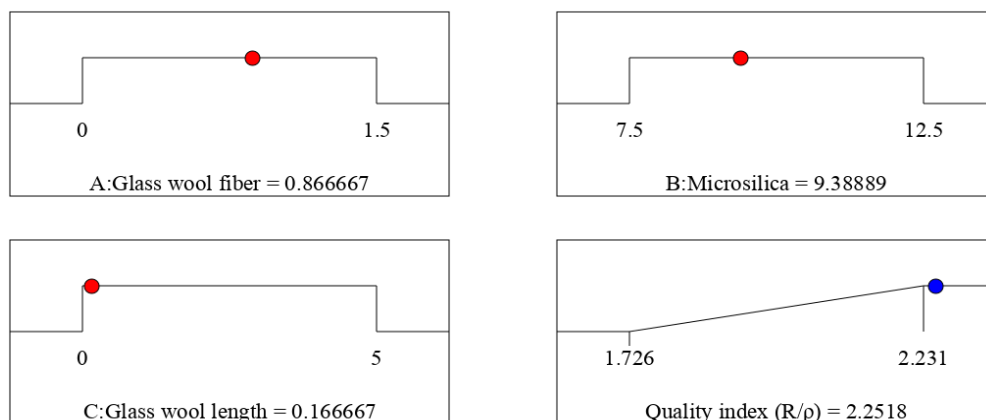


Fig. 12. (a) Three-dimensional response surface of glass wool fiber content and microsilica content; (b) glass wool fiber content and fiber length; and (c) microsilica content and glass wool fiber length.

The optimization results obtained from the RSM model are presented in Fig. 13. Two different optimum conditions should be clearly distinguished. The highest experimentally measured compressive strength (40.0 MPa) was obtained for the mixture containing 10% microsilica, 0.5% glass wool fibers, and a fiber length of 27.5 mm.



Desirability = 1.000
Solution 17 out of 100

(a)

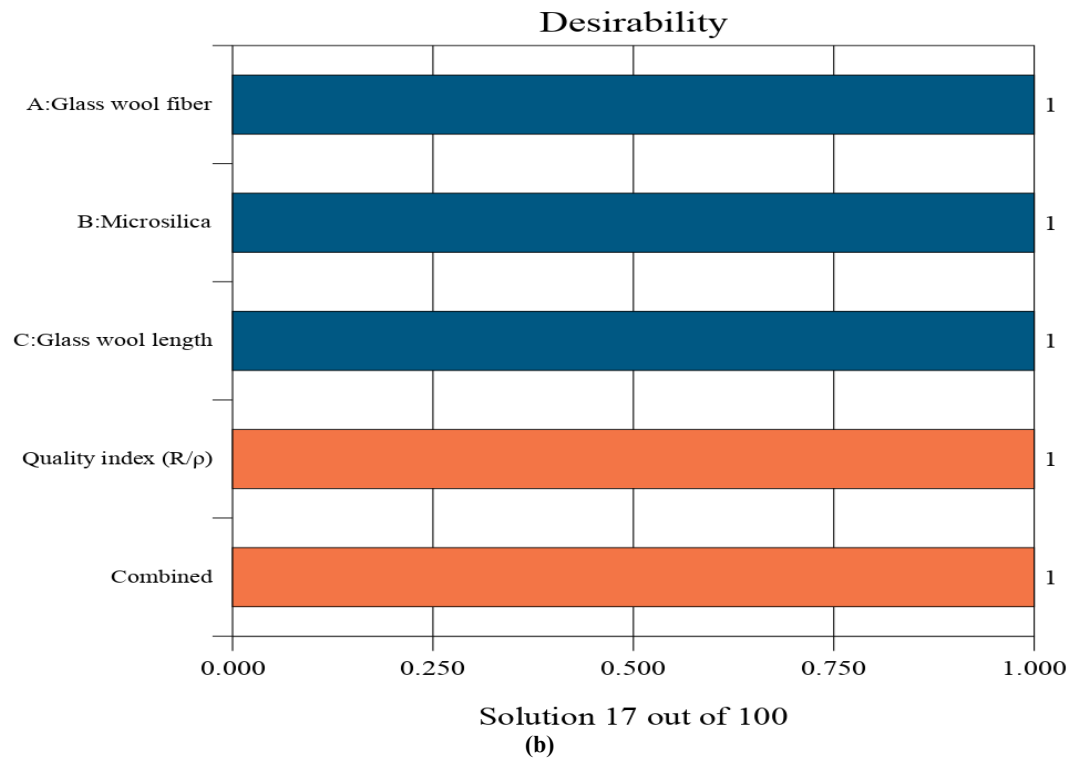


Fig. 13. Results of the RSM optimization: (a) numerical optimization showing the optimum levels of glass wool fiber content, fiber length, and microsilica content for maximizing the Quality Index (R/ρ); and (b) desirability function corresponding to the optimum solution.

However, the multi-objective optimization performed using the RSM model predicted a different optimum mixture containing approximately 9.39% microsilica and 0.87% glass wool fibers, which maximized the quality index ($R/\rho \approx 2.25$). This difference is expected because the experimental optimum corresponds to maximizing compressive strength alone, whereas the RSM optimization simultaneously considers both compressive strength and concrete density. Consequently, the optimum quality index represents the highest strength-to-density efficiency rather than the highest compressive strength. Accordingly, the experimentally determined optimum mixture and the RSM-optimized mixture represent two different optimization objectives derived from the same experimental database.

Fig. 14 presents the influence of the investigated variables on the desirability function used during numerical optimization. The desirability value approaches unity within the optimum design region, indicating that the selected combination of variables simultaneously satisfies the optimization criteria defined for the response variable.

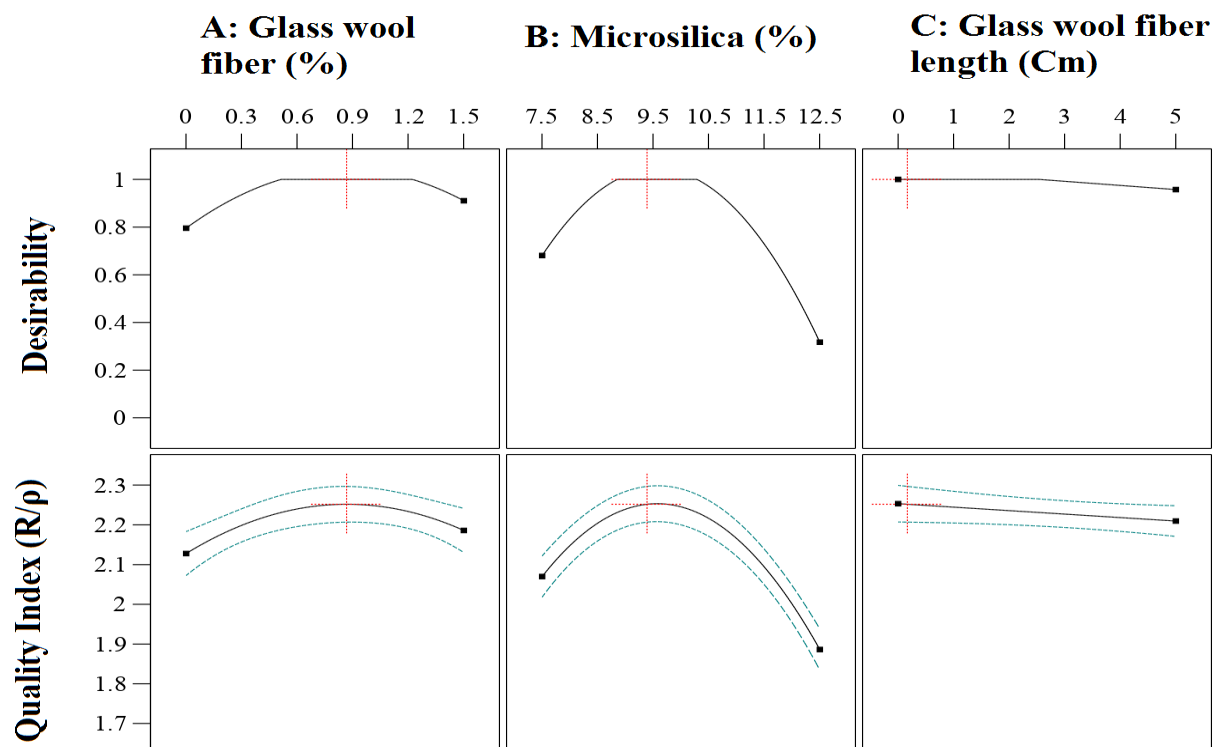


Fig. 14. Main effect plots showing the influence of glass wool fiber content (%), microsilica content (%), and glass wool fiber length (Cm) on the desirability function.

The contour plots in Fig. 15 illustrate the interaction effects among the variables in the design space. To evaluate the predictive capability of the developed RSM model, three additional concrete mixtures outside the model calibration dataset were experimentally tested. The differences between the experimentally measured and RSM-predicted quality index values were less than 4%, confirming the satisfactory predictive capability and robustness of the developed regression model within the investigated design space. Nevertheless, additional validation using independent experimental datasets covering a wider range of mixture proportions is recommended to further improve the general applicability of the proposed predictive model.

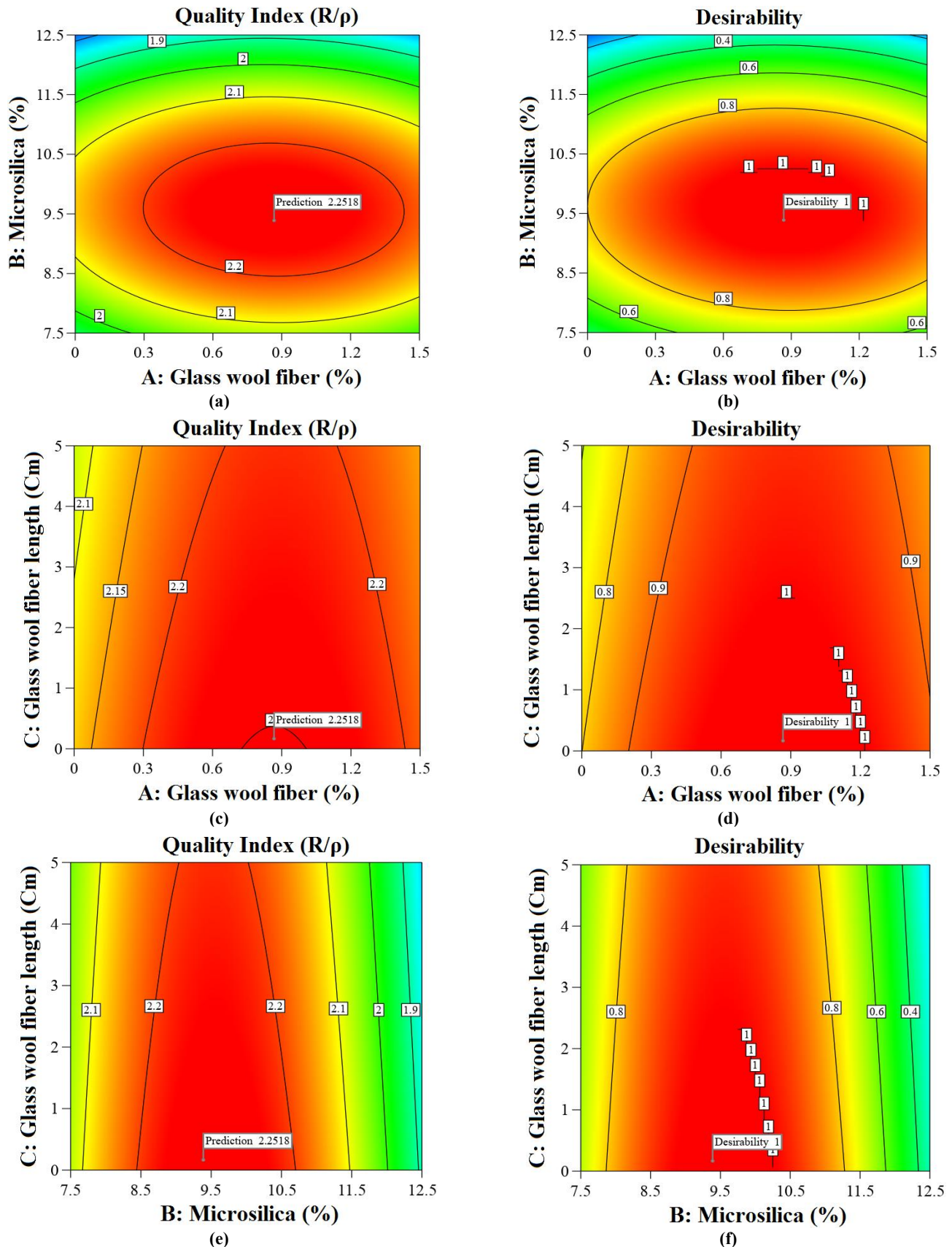


Fig. 15. Contour plots of the response and desirability functions for the investigated factor interactions: (a) quality index (R/ρ) for factors A and B; (b) desirability for factors A and B; (c) quality index (R/ρ) for factors A and C; (d) desirability for factors A and C; (e) quality index (R/ρ) for factors B and C; and (f) desirability for factors B and C.

Previous studies have reported that the incorporation of approximately 5% microsilica can enhance compressive strength by nearly 12% in fiber-reinforced concrete [53]. In the present study, the combination of 10% microsilica and 0.5% Glass wool fibers resulted in a 7.5% increase in compressive strength of lightweight concrete. The difference is mainly attributed to the higher porosity of perlite aggregates and reduced matrix continuity in lightweight concrete. Additionally, the lower water-to-cement ratio (0.335) and reduced density limit the absolute load-bearing capacity. Nevertheless, the results confirm the beneficial role of microsilica in densifying the matrix and improving the interfacial transition zone (ITZ), which is consistent with the findings of Singaravel et al. (2024) [52].

The fiber content analysis revealed an optimum value of approximately 0.5%, beyond which mechanical performance decreased due to fiber agglomeration and reduced workability. This behavior is consistent with previous studies on fiber-reinforced concrete systems [40]. The increase in fiber content beyond 1% led to strength reduction and higher porosity due to non-uniform dispersion and matrix discontinuity. Therefore, simultaneous optimization of microsilica and fiber content is essential not only for compressive strength but also for the mechanical efficiency index (R/ρ) [45]. Overall, the results demonstrate that optimizing microsilica and glass wool fiber contents effectively improves the mechanical efficiency of lightweight concrete.

4. Conclusions

Based on the experimental investigation and response surface methodology (RSM) analysis, the following conclusions can be drawn:

- Thirty perlite lightweight concrete mixtures containing different microsilica contents (7.5-12.5%), glass wool fiber dosages (0-1.5 vol%), and fiber lengths (5-50 mm) were experimentally evaluated to investigate their effects on compressive strength, stress-strain behavior, energy absorption, and quality index (R/ρ).
- The highest compressive strength (40.0 MPa) was obtained for the mixture containing 10% microsilica and 0.5% glass wool fibers with a fiber length of 27.5 mm, corresponding to an approximately 7.5% increase compared with the control mixture.
- Increasing the glass wool fiber dosage improved ductility, ultimate strain, and post-peak energy absorption. The greatest deformation capacity was observed at 1.5% fiber dosage; however, excessive fiber addition reduced workability and matrix homogeneity, leading to a slight reduction in compressive strength.
- The incorporation of approximately 10% microsilica significantly improved the mechanical performance through matrix densification, pore refinement, and enhancement of the interfacial transition zone (ITZ). Higher replacement levels (12.5%) resulted in a reduction in mechanical performance, mainly due to increased water demand and reduced stress redistribution capacity.
- ANOVA results confirmed that microsilica content (factor B) together with the quadratic effects of fiber dosage (A^2) and microsilica content (B^2) significantly influenced the quality index ($p < 0.05$), whereas the linear effects of fiber length and the interaction terms were statistically insignificant within the investigated design space.
- The experimentally determined optimum mixture for maximum compressive strength differed from the RSM-predicted optimum for the quality index. While the RSM optimization predicted a mixture containing approximately 9.39% microsilica and 0.87% glass wool fibers that yielded the highest quality index ($R/\rho \approx 2.25$), the experimental mixture produced the maximum compressive strength. This distinction demonstrates that maximizing compressive strength and maximizing strength-to-density efficiency are two different optimization objectives.
- SEM observations confirmed that the combined incorporation of microsilica and glass wool fibers improved matrix compactness, strengthened the interfacial transition zone, and promoted effective crack-bridging mechanisms, which explain the observed improvements in ductility, post-peak behavior, and energy absorption capacity.
- The novelty of this study lies in integrating experimental investigation with RSM-based multi-objective optimization to distinguish between experimentally measured optimum mechanical performance and mathematically predicted optimum strength-to-density efficiency. The proposed approach provides a practical framework for optimizing structural lightweight perlite concrete within the investigated material ranges. These conclusions are applicable only to the material ranges and experimental conditions considered in this study.

5. Limitations and recommendations

- This study was conducted under laboratory conditions and primarily focused on compressive strength and quality index. Therefore, long-term durability, environmental exposure, and economic considerations were not investigated.
- In the RSM analysis, glass wool fiber dosage and fiber length were treated as continuous variables, whereas the experimental program was conducted only at discrete factor levels. Consequently, the predicted optimum values (including the 0.87% fiber dosage and intermediate fiber lengths) represent mathematical interpolations within the investigated design space rather than experimentally verified optimum mixtures. Therefore, additional experiments are recommended to validate these predicted optimum conditions.
- Only one type of lightweight aggregate (perlite) and one type of glass wool fiber were employed in this study. Future

research is recommended to investigate other lightweight aggregates and fiber types, as well as the effects of environmental conditions such as freeze-thaw cycles, sulfate and alkaline exposure, and alternative pozzolanic materials on the performance of lightweight concrete.

Statements & declarations

Author contributions

Hooman Yaghoobipour: Conceptualization, Methodology, Investigation, Formal analysis, Data curation, Visualization, Writing - Original Draft, Writing - Review & Editing.

Hamidreza Tavakoli: Conceptualization, Methodology, Validation, Resources, Supervision, Project administration, Writing - Review & Editing.

Funding

This research received no specific grant from any funding agency.

Data availability

The data presented in this study are available from the corresponding author upon reasonable request..

Declarations

The authors declare no conflict of interest.

References

- [1] Xiaopeng, L. Structural lightweight concrete with pumice aggregate [Master's Thesis]. Singapore (SG): National University of Singapore; 2005.
- [2] Shah, S. N., Tan, T. H., Tey, O. W., Leong, G. W., Chin, Y. S., Yuen, C. W., Mo, K. H. Aerogel and expanded perlite incorporated lightweight cementitious composites containing crushed glass: Evaluation of the drying shrinkage and alkali-silica expansion. *Science Progress*, 2022; 105: 00368504221091186. doi:10.1177/00368504221091186.
- [3] Najaf, E., Orouji, M., Zahrai, S. M. Improving nonlinear behavior and tensile and compressive strengths of sustainable lightweight concrete using waste glass powder, nanosilica, and recycled polypropylene fiber. *Nonlinear Engineering*, 2022; 11: 58–70. doi:10.1515/nleng-2022-0008.
- [4] Zhang, W., Zhang, Y., Bao, S., Yan, K., Duan, L., Zeng, K. Mechanical strength and microstructure of ultra-high-performance cementitious composite with glass powder substituted cement/silica fume. *Structural Concrete*, 2024; 25: 3662–3681. doi:10.1002/suco.202300876.
- [5] Bilal, M. M., Shahab, K., Hashmi, A. F., Umar, A. Effect of Micro-Silica on Fresh and Hardened Properties of Self-Compacting Concrete Reinforced with Glass and Polyvinyl Alcohol Fibres. *Construction*, 2022; 2: 83 – 92. doi:10.15282/construction.v2i2.8746.
- [6] Zeyad, A. M., Hakeem, I. Y., Amin, M., Tayeh, B. A., Agwa, I. S. Effect of aggregate and fibre types on ultra-high-performance concrete designed for radiation shielding. *Journal of Building Engineering*, 2022; 58: 104960. doi:10.1016/j.job.2022.104960.
- [7] Abdelsalam, B. A., Saad, M. A., Amin, M., Agwa, I. S. Flexural performance of concrete beams reinforced with fiber ropes as partial sustainable reinforcement. *Innovative Infrastructure Solutions*, 2025; 10: 433. doi:10.1007/s41062-025-02223-3.
- [8] Dziomdziora, P., Smarzewski, P. Effect of Hybrid Fiber Compositions on Mechanical Properties and Durability of Ultra-High-Performance Concrete: A Comprehensive Review. *Materials*, 2025; 18: 2426. doi:10.3390/ma18112426.
- [9] Deng, M., Han, J., Liu, H., Qin, M., Liang, X. Analysis of Compressive Toughness and Deformability of High Ductile Fiber Reinforced Concrete. *Advances in Materials Science and Engineering*, 2015; 2015: 384902. doi:10.1155/2015/384902.
- [10] Altalib, F., Tavakoli, H. R., Hashemi, S. K. The Post-fire Behavior of Lightweight Structural Concrete is Improved by Nano-SiO₂ and Steel Fibers. *International Journal of Engineering*, 2023; 36: 1942–1960. doi:10.5829/ije.2023.36.11b.01.
- [11] Fallahtabar Shiade, M., Tavakoli, H. Estimation of Mechanical and Durability Properties of Self-Compacting Concrete with Fibers Using Ultrasonic Pulse Velocity. *Journal of Rehabilitation in Civil Engineering*, 2018; 6: 43–53. doi:10.22075/jrce.2018.798.1099.
- [12] Akbarpour, S., Dabbagh, H., Tavakoli, H. R. The Effects of Steel Fiber and Nano-SiO₂ on the Cyclic Flexural Behavior of Reinforced LWAC Beams. *KSCE Journal of Civil Engineering*, 2018; 22: 3919–3930. doi:10.1007/s12205-017-0920-3.
- [13] Tavakoli, H. Prediction of Combined Effects of Fibers and Nano-Silica on the Mechanical Properties of Self-Compacting Concrete Using Artificial Neural Network. *Latin American Journal of Solids and Structures*, 2014; 11: 1906–1923.
- [14] Shafigh, P., Chai, L. J., Mahmud, H. B., Nomeli, M. A. A comparison study of the fresh and hardened properties of normal weight and lightweight aggregate concretes. *Journal of Building Engineering*, 2018; 15: 252–260. doi:10.1016/j.job.2017.11.025.

- [15] Shafigh, P., Mahmud, H. B., Jumaat, M. Z. B., Ahmmad, R., Bahri, S. Structural lightweight aggregate concrete using two types of waste from the palm oil industry as aggregate. *Journal of Cleaner Production*, 2014; 80: 187–196. doi:10.1016/j.jclepro.2014.05.051.
- [16] Shannag, M. J. Characteristics of lightweight concrete containing mineral admixtures. *Construction and Building Materials*, 2011; 25: 658–662. doi:10.1016/j.conbuildmat.2010.07.025.
- [17] Lim, C.-S., Jang, D.-S., Kim, J.-C., Kim, H.-S., Lee, J.-J. A Study on the Applicability of Waste Glass Wool and Waste Mineral Wool as Fiber Reinforcement. *Applied Sciences*, 2023; 13: 10738. doi:10.3390/app131910738.
- [18] Jeon, C.-K., Lee, J.-S., Chung, H., Kim, J.-H., Park, J.-P. A Study on Insulation Characteristics of Glass Wool and Mineral Wool Coated with a Polysiloxane Agent. *Advances in Materials Science and Engineering*, 2017; 2017: 3938965. doi:10.1155/2017/3938965.
- [19] AlTawaiha, H., Alhomaidat, F., Eljufout, T. A Review of the Effect of Nano-Silica on the Mechanical and Durability Properties of Cementitious Composites. *Infrastructures*, 2023; 8: 132. doi:10.3390/infrastructures8090132.
- [20] Mrema, A. H., Noh, S.-H., Kwon, O.-S., Lee, J.-J. Performance of Glass Wool Fibers in Asphalt Concrete Mixtures. *Materials*, 2020; 13: 4699. doi:10.3390/ma13214699.
- [21] Gowri, R., Mary, M. Effect of glass wool fibres on mechanical properties of concrete. *International Journal of Engineering Trends and Technology*, 2013; 4: 3045–3048. doi:10.14445/22315381/IJETT-V4I7P153.
- [22] Amir, N., Jalil, A. N. A., Ahmad, F. Characterization and study of char performance of glass wool and rockwool hybrid fibre reinforced intumescent coatings. *ARNP Journal of Engineering and Applied Sciences*, 2016; 11: 12268–12274.
- [23] ASTM International. ASTM C330/C330M-23: Standard Specification for Lightweight Aggregates for Structural Concrete. West Conshohocken (PA): ASTM; 2023. doi:10.1520/C0330_C0330M-23.
- [24] ASTM International. ASTM C33/C33M-18: Standard Specification for Concrete Aggregates. West Conshohocken (PA): ASTM; 2018. doi:10.1520/C0033_C0033M-18.
- [25] ASTM International. ASTM C567-05a: Standard Test Method for Determining Density of Structural Lightweight Concrete. West Conshohocken (PA): ASTM; 2005. doi:10.1520/C0567-05A.
- [26] ASTM International. ASTM C496-96: Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens. West Conshohocken (PA): ASTM; 1996. doi:10.1520/C0496-96.
- [27] ASTM International. ASTM C469-02: Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression. West Conshohocken (PA): ASTM; 2002. doi:10.1520/C0469-02.
- [28] ASTM International. ASTM C39/C39M-21: Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. West Conshohocken (PA): ASTM; 2021. doi:10.1520/C0039_C0039M-21.
- [29] American Concrete Institute (ACI). ACI 211.2-98: Standard Practice for Selecting Proportions for Structural Lightweight Concrete. Farmington Hills (MI): ACI; 1998.
- [30] Li, H., Jin, P., Yan, C., Zhang, N., Li, L. Impact of polyethylene fiber and microsilica on fracture properties of high strength high toughness geopolymer concrete (HSHTGC). *Developments in the Built Environment*, 2024; 18: 100399. doi:10.1016/j.dibe.2024.100399.
- [31] Abbas, S. N., Qureshi, M. I., Alkharisi, M. K., Alturki, M., Ahmad, Z. Combined effect of silica fume and various fibers on fresh and hardened properties of concrete incorporating HDPE aggregates. *Construction and Building Materials*, 2024; 445: 137940. doi:10.1016/j.conbuildmat.2024.137940.
- [32] Stat-Ease, Inc. Design-Expert®. Version 13. Minneapolis (MN): Stat-Ease, Inc.; 2022.
- [33] Mazilu, C., Deju, R., Georgescu, D. P., Apostu, A., Barbu, A. Effects of Micro- and Nanosilica on the Mechanical and Microstructural Characteristics of Some Special Mortars Made with Recycled Concrete Aggregates. *Materials*, 2024; 17: 2791. doi:10.3390/ma17122791.
- [34] Ajileye, F. V. Investigations on Microsilica (Silica Fume) As Partial Cement Replacement in Concrete. *Global Journals of Research in Engineering*, 2012; 12: 17–23.
- [35] Ahmadi, N., Yazdandoust, M., Yazdani, M. Simultaneous Effect of Aggregate and Cement Matrix on the Performance of High Strength Concrete. *Journal of Rehabilitation in Civil Engineering*, 2021; 9: 26–39. doi:10.22075/jrce.2021.20803.1431.
- [36] Arman, A., Kuse Sedan, E., Shafei, E. Evaluating the Influence of Micro Silica Content on Concrete Mechanical Properties: An Experimental Study. In: 4th International Congress on Civil Engineering, Architecture, Building Materials and Environment; 2025 Mar 10; Helsinki, Finland. p. 1–11.
- [37] Faghihmaleki, H., Nazari, H. Laboratory study of metakaolin and microsilica effect on the performance of high-strength concrete containing Forta fibers. *Advances in Bridge Engineering*, 2023; 4: 11. doi:10.1186/s43251-023-00091-4.
- [38] Zhen, H., Xiong, Z., Song, Y., Li, L., Qiu, Y., Zou, X., Chen, B., Chen, D., Liu, F., Ji, Y. Early mechanical performance of glass fibre-reinforced manufactured sand concrete. *Journal of Building Engineering*, 2024; 83: 108440. doi:10.1016/j.jobee.2024.108440.

- [39] Krishna, A. S., Kumar, K. R., VishnuPriyan, M. A state-of-the-art analysis of repair and rehabilitation of masonry structures by using geopolymer mortar. *Discover Applied Sciences*, 2025; 7: 307. doi:10.1007/s42452-025-06799-4.
- [40] Kasagani, H., Rao, C. B. K. Effect of graded fibers on stress strain behaviour of glass fiber reinforced concrete in tension. *Construction and Building Materials*, 2018; 183: 592–604. doi:10.1016/j.conbuildmat.2018.06.193.
- [41] Yahiaoui, D., Saadi, M., Bouzid, T. Compressive Behavior of Concrete Containing Glass Fibers and Confined with Glass FRP Composites. *International Journal of Concrete Structures and Materials*, 2022; 16: 37. doi:10.1186/s40069-022-00525-9.
- [42] Lv, H., Li, L., Zhu, W., Li, X., Wang, D., Ling, Z., Feng, P., Liu, F. Effects of Steel and Glass Fibers on the Compressive Behavior of Rubberized Concrete: An Experimental Study and Constitutive Modeling. *Buildings*, 2024; 14: 3474. doi:10.3390/buildings14113474.
- [43] Özodabaş, A. The ductility performance of concrete using glass fiber mesh in beam specimens. *Applied Rheology*, 2023; 33: 1–8. doi:10.1515/arh-2023-0109.
- [44] Lu, M., Wu, Z., Hao, Z., Liu, L. Experimental Investigation of the Mechanical Behavior of the Strain Isolation Pad in Thermal Protection Systems under Tension. *Aerospace*, 2024; 11: 305. doi:10.3390/aerospace11040305.
- [45] Ahmad, J., González-Lezcano, R. A., Majdi, A., Ben Kahla, N., Deifalla, A. F., El-Shorbagy, M. A. Glass Fibers Reinforced Concrete: Overview on Mechanical, Durability and Microstructure Analysis. *Materials*, 2022; 15: 5111. doi:10.3390/ma1515111.
- [46] Arsalan, M. E., Aykanat, B., Emiroglu, M. Effects of glass fiber usage on fracture energy and mechanical behavior of concrete: An experimental approach. *Journal of Structural Engineering & Applied Mechanics*, 2023; 6: 70–83. doi:10.31462/jseam.2023.01070083.
- [47] Banerjee, P., Habib, M. S., Kuckian, S., Balushi, Y. A., Hashami, S. A. Effects of Glass Fibre on the Strength and Properties of Concrete. In: *2023 International Conference on Sustainable Technologies in Civil and Environmental Engineering (ICSTCE 2023)*; 2023 Jun 15–16; Pimpri, India. p. 1–11. doi:10.1051/e3sconf/202340503003.
- [48] Qiao, J., Zhang, Q., Wu, C., Wu, G., Li, L. Effects of Fiber Volume Fraction and Length on the Mechanical Properties of Milled Glass Fiber/Polyurea Composites. *Polymers*, 2022; 14: 3080. doi:10.3390/polym14153080.
- [49] Yahya, Y. M., Galeb, A. C. Key effects on the structural behavior of fiber-reinforced lightweight concrete-ribbed slabs: A review. *Open Engineering*, 2024; 14: 20240054. doi:doi:10.1515/eng-2024-0054.
- [50] Infant Alex, X., Arunachalam, K. Flexural behavior of fiber reinforced lightweight concrete. *Revista de la Construcción*, 2019; 18: 536–544. doi:10.7764/RDLC.18.3.536.
- [51] Raza, S. S., Amir, M. T., Azab, M., Ali, B., Abdallah, M., El Ouni, M. H., Elhag, A. B. Effect of micro-silica on the physical, tensile, and load-deflection characteristics of micro fiber-reinforced high-performance concrete (HPC). *Case Studies in Construction Materials*, 2022; 17: e01380. doi:10.1016/j.cscm.2022.e01380.
- [52] Singaravel, D. A., Veerapandian, P., Rajendran, S., Dhairiyasamy, R. Enhancing high-performance concrete sustainability: integration of waste tire rubber for innovation. *Scientific Reports*, 2024; 14: 4635. doi:10.1038/s41598-024-55485-9.
- [53] Agarwal, A., Shekhawat, R. S. Experimental Study of Glass Fiber Reinforced Concrete Incorporating Micro Silica. *Journal of Scientific Research and Reports*, 2023; 29: 90–100. doi:10.9734/JSRR/2023/v29i71763.