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EVALUATION OF THE MECHANICAL PERFORMANCE OF FOAMED CONCRETE USING THE SPECIFIC COMPRESSIVE STRENGTH-TO-DRY DENSITY RATIO

Summary: Owing to its low density, self-compacting capability, and thermal insulation properties, foamed concrete is widely used in lightweight construction. However, achieving an optimal balance between mechanical strength and dry density remains a major challenge in mix design. This study experimentally evaluated 32 foamed concrete mixtures incorporating different foaming agent types, cement types, polypropylene fibers, supplementary cementitious materials, and superplasticizer. Mixture performance was assessed using compressive strength, dry density, and the Specific Compressive Strength-to-Dry Density Index, which reflects both load-bearing capacity and lightweight efficiency. The results showed that the investigated variables affected the performance index to different extents, with cement content, foaming agent type, and superplasticizer exhibiting the greatest influence. The optimum mixture achieved a compressive strength of 4.2 MPa, a dry density of 683 kg/m³, and the highest performance index of 6.1. These findings provide practical guidance for optimizing low-density foamed concrete with improved mechanical performance of foamed concrete.

Keywords: compressive strength, dry density, specific compressive strength-to-dry density index, foaming agent, polypropylene fibers, superplasticizer

PROCENA MEHANIČKIH SVOJSTAVA PENOBETONA PRIMENOM ODNOSA ČVRSTOĆE PRI PRITISKU I ZAPREMINSKE MASE U SUVOM STANJU

Rezime: Zahvaljujući svojoj maloj zapreminskoj masi, mogućnosti samougradnje i svojstvima toplotne izolacije, penobeton se široko koristi kod lakih građevinskih konstrukcija. Međutim, postizanje optimalne ravnoteže između mehaničke čvrstoće i zapreminske mase u suvom stanju ostaje glavni izazov pri projektovanju mešavina. Istraživanja se odnose na 32 mešavine penobetona sa različitim vrstama penušavaca, cementa, polipropilenskim vlaknima, mineralnim dodacima i superplastifikatorima. Performanse mešavina procenjene su na osnovu pritisne čvrstoće, zapreminske mase u suvom stanju i indeksa specifičnog odnosa pritisne čvrstoće i zapreminske mase, koji odražava i nosivost i efikasnost olakšavanja konstrukcije. Rezultati su pokazali da ispitivane promenljive utiču na indeks performansi u različitoj meri, pri čemu su sadržaj cementa, vrsta penušavca i superplastifikator pokazali najveći uticaj. Optimalna mešavina postigla je pritisnu čvrstoću od 4,2 MPa, zapreminsku masu u suvom stanju od 683 kg/m³ i najviši indeks performansi od 6,1. Dobijeni rezultati pružaju praktične smernice za optimizaciju penobetona male zapreminske mase u cilju poboljšanja mehaničkih karakteristika peno betona.

Ključne reči: čvrstoća pri pritisku, zapreminska masa, indeks specifičnog odnosa pritisne čvrstoće i zapreminske mase, penušavac, polipropilenska vlakna, superplastifikato.

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1. INTRODUCTION

The construction industry requires lightweight, cost-effective, and sustainable materials that can reduce the dead load of structures while maintaining adequate mechanical performance[1]. Owing to its low density, high flowability, self-compacting capability, thermal insulation properties, and ease of placement, foamed concrete has emerged as a promising material for a wide range of non-structural and semi-structural applications, including floor and roof filling, lightweight masonry blocks, void filling, and trench reinstatement[2][3]. However, increasing the foam volume and reducing density generally lead to a significant reduction in compressive strengtha[4]. Therefore, the selection of an optimum mix design should be based on achieving an appropriate balance among compressive strength, dry density, and cement consumption, rather than simply maximizing strength.

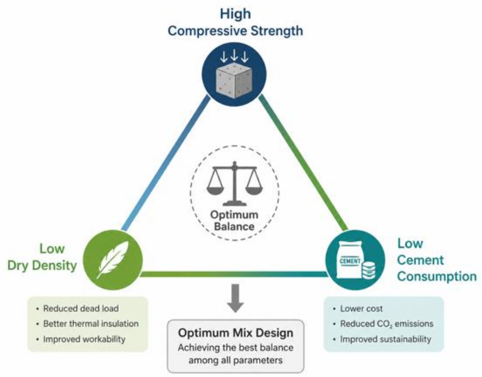

Figure 1:Design objectives for optimizing low-density foamed concrete mixtures.

In a study conducted by Zhang et al. (2026), the mechanical behavior of carbon nanotube (CNT)-modified foamed concrete was investigated using 16 experimental mix designs. The experimental variables included fly ash replacement ratio, water-to-binder ratio, aggregate-to-binder ratio, CNT dosage, and foam volume fraction. Cylindrical specimens (50 × 100 mm) were subjected to uniaxial compressive strength testing after 28 days of standard curing. The reported apparent density and 28-day compressive strength ranged from 690 to 1380 kg/m³ and 2.382 to 18.381 MPa, respectively. The calculated compressive strength-to-apparent density index varied between 4.98 and 6.19 MPa/(kg/m³), with the highest value achieved for the mixture containing 80% fly ash replacement, 0.10% CNT, and 50% foam volume. The results indicated that foam volume fraction, water-to-binder ratio, and aggregate-to-binder ratio were the most influential parameters governing both density and compressive strength, whereas increasing the foam content generally reduced both properties. Although the incorporation of CNTs contributed positively to improving the strength–density balance, the reported performance index should be interpreted with caution because it was calculated using apparent density rather than oven-dry density, and no drying procedure to constant mass was reported.[5]

Zhou et al. (2026) investigated the effect of bamboo bio-aggregates as a sustainable replacement for natural sand in foamed concrete through an experimental program examining different aggregate sizes and replacement ratios. The study evaluated the mechanical, thermal, acoustic, and environmental performance of the developed mixtures. The results showed that the dry density ranged from 1003 to 1351 kg/m³, while the maximum compressive strength reached 11.45 MPa with 5% fine bamboo aggregate replacement. In addition to improving compressive and flexural strengths, the incorporation of bamboo aggregates significantly enhanced thermal insulation and sound absorption, while reducing the carbon footprint by up to 18% compared with conventional foamed concrete. Based on the reported density and compressive strength, the Specific Compressive Strength-to-Dry Density Index reached an estimated maximum value of 11.42, indicating that the optimized bamboo-based foamed concrete achieved an excellent balance between lightweight characteristics and mechanical performance. These findings demonstrate that bamboo bio-aggregates represent a promising sustainable alternative for producing high-performance, low-density foamed concrete suitable for non-structural and semi-structural construction applications[6].

In a study conducted by Othman et al. (2021), the effects of foam dosage on the mechanical performance of foamed concrete were experimentally investigated by evaluating workability, density, and compressive strength. The results showed that increasing the foam dosage from 20% to 35% reduced the dry density from 1734 to 1409 kg/m³ and the 28-day compressive strength from 8.8 to 3.0 MPa. Based on the reported data, the Specific Compressive Strength-to-Dry Density Index ranged from 2.13 to 5.07, with the highest value corresponding to the 20% foam dosage mixture and the lowest value to the 35% foam dosage mixture. The study demonstrated that increasing foam content effectively decreases density but causes a more pronounced reduction in compressive strength, resulting in a lower mechanical efficiency. Consequently, a 25% foam dosage was recommended as the optimum mixture because it provided a balanced combination of 1625 kg/m³ dry density, 7.5 MPa compressive strength, satisfactory workability, and an acceptable performance index[7].

2. COMPONENT MATERIALS AND TESTING METHODS

In the present study, the performance of low-density foamed concrete was evaluated through an experimental investigation involving 32 mix designs. The investigated variables included foaming agent type, cement type, supplementary cementitious materials (SCMs), polypropylene fibers (PP fibers), superplasticizer, and cement content. Compressive strength and oven-dry density were selected as the primary performance indicators. In addition, the Specific Compressive Strength-to-Dry Density Index and cement utilization efficiency were adopted to evaluate the overall efficiency of the proposed mixtures.

The primary objective of this study was to identify optimum low-density foamed concrete mixtures capable of achieving superior mechanical efficiency while maintaining a low dry density. To this end, the influence of the investigated mix-design parameters on the Specific Compressive Strength-to-Dry Density Index was systematically examined. This index provides an effective criterion for comparing the performance of lightweight mixtures, as it simultaneously accounts for both load-bearing capacity and material density.

The experimental program was conducted in two successive phases. In the first phase, 16 mix designs were produced using different combinations of foaming agent type, cement type, the presence or absence of supplementary cementitious materials, and polypropylene fibers. Both synthetic and protein-based foaming agents, as well as Ordinary Portland Cement (OPC) and Portland Pozzolanic Cement (PPC), were investigated. Furthermore, mixtures with and without supplementary cementitious materials and polypropylene fibers were prepared to evaluate the influence of these constituents on the mechanical and physical properties of foamed concrete. The primary objective of this phase was to provide a comprehensive assessment of the effects of material composition on foamed concrete performance.

The second phase also consisted of 16 mix designs and focused on the practical optimization of foamed concrete mixtures. In this phase, foaming agent type, cement content, polypropylene fiber dosage, and superplasticizer incorporation were selected as the principal variables. Cement contents of 250 and 300 kg/m³ were adopted to investigate the influence of binder content on compressive strength development. Polypropylene fibers were incorporated at dosages of 240 and 480 g/m³, while mixtures were prepared both with and without a superplasticizer. Similar to the first phase, both synthetic and protein-based foaming agents were employed.

Table 1: Experimental design variables and their corresponding levels for Phases I and II

Phase IMix	Description	Phase IIMix	Description
1	Chemical, OPC, without SCM, no PP fiber	**17**	Chemical, without SP, 250 kg/m³ cement, 240 g/m³ PP fiber
2	Chemical, OPC, without SCM, 200 g/m³ PP fiber	**18**	Chemical, without SP, 300 kg/m³ cement, 240 g/m³ PP fiber
3	Chemical, OPC, with SCM, no PP fiber	**19**	Chemical, without SP, 250 kg/m³ cement, 480 g/m³ PP fiber
4	Chemical, OPC, with SCM, 200 g/m³ PP fiber	**20**	Chemical, without SP, 300 kg/m³ cement, 480 g/m³ PP fiber
5	Chemical, PPC, without SCM, no PP fiber	**21**	Chemical, with SP, 250 kg/m³ cement, 240 g/m³ PP fiber
6	Chemical, PPC, without SCM, 200 g/m³ PP fiber	**22**	Chemical, with SP, 300 kg/m³ cement, 240 g/m³ PP fiber
7	Chemical, PPC, with SCM, no PP fiber	**23**	Chemical, with SP, 250 kg/m³ cement, 480 g/m³ PP fiber
8	Chemical, PPC, with SCM, 200 g/m³ PP fiber	**24**	Chemical, with SP, 300 kg/m³ cement, 480 g/m³ PP fiber
9	Protein, OPC, without SCM, no PP fiber	**25**	Protein, without SP, 250 kg/m³ cement, 240 g/m³ PP fiber
10	Protein, OPC, without SCM, 200 g/m³ PP fiber	**26**	Protein, without SP, 300 kg/m³ cement, 240 g/m³ PP fiber
11	Protein, OPC, with SCM, no PP fiber	**27**	Protein, without SP, 250 kg/m³ cement, 480 g/m³ PP fiber
12	Protein, OPC, with SCM, 200 g/m³ PP fiber	**28**	Protein, without SP, 300 kg/m³ cement, 480 g/m³ PP fiber
13	Protein, PPC, without SCM, no PP fiber	**29**	Protein, with SP, 250 kg/m³ cement, 240 g/m³ PP fiber
14	Protein, PPC, without SCM, 200 g/m³ PP fiber	**30**	Protein, with SP, 300 kg/m³ cement, 240 g/m³ PP fiber
15	Protein, PPC, with SCM, no PP fiber	**31**	Protein, with SP, 250 kg/m³ cement, 480 g/m³ PP fiber
16	Protein, PPC, with SCM, 200 g/m³ PP fiber	**32**	Protein, with SP, 300 kg/m³ cement, 480 g/m³ PP fiber

The selected experimental variables were chosen based on their practical significance in the production of foamed concrete for lightweight construction applications. Particular emphasis was placed on achieving an appropriate balance between compressive strength and oven-dry density, as these parameters play a decisive role in the engineering performance of foamed concrete. Accordingly, the experimental matrix was designed to facilitate the identification of mixtures exhibiting high mechanical efficiency while maintaining low density. In total, 32 mix designs were prepared and experimentally evaluated. For each mixture, compressive strength and oven-dry density were measured, and the resulting data were analyzed to assess the influence of different material combinations and to identify the optimum mix designs.

Figure 2: Foamed concrete specimen under the compressive strength testing machine.

3. RESULTS AND DISCUSSION

To simultaneously evaluate the load-bearing capacity and lightweight performance of foamed concrete, the Specific Compressive Strength-to-Dry Density Index was calculated as:

$$I = \frac{f_c}{\rho_d} * 1000$$

where f_c is the compressive strength (MPa) and ρ_d is the oven-dry density (kg/m³).

This index represents the mechanical efficiency of foamed concrete, with higher values indicating greater compressive strength per unit weight and, consequently, superior lightweight structural performance. The calculated values ranged from 1.977 to 6.102, corresponding to Mix 12 and Mix 22, respectively. Such a wide variation demonstrates the significant influence of mix-design parameters on the microstructure, pore characteristics, cement paste continuity, and ultimately the mechanical efficiency of foamed concrete. Therefore, the Specific Compressive Strength-to-Dry Density Index provides a more comprehensive criterion than compressive strength alone for evaluating lightweight foamed concrete, as it simultaneously considers both strength and density.

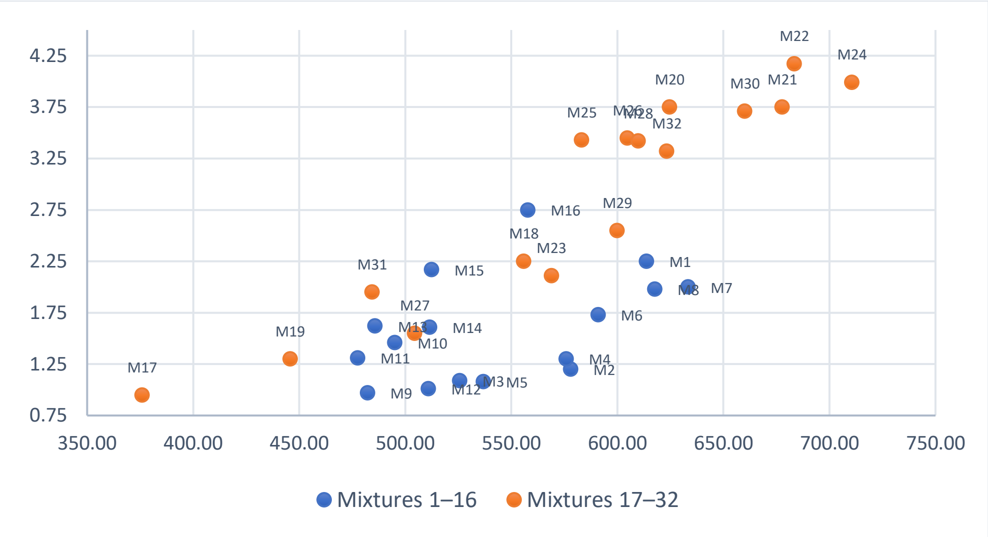

Figure 3: Average compressive strength versus dry density for 32 mixtures.

In the first experimental series, the use of the protein-based foaming agent reduced the average oven-dry density from approximately 584 to 504 kg/m³ compared with the synthetic foaming agent. Although the average compressive strengths of the two groups were relatively similar, the protein-based foam exhibited a higher strength-to-density index.

- Average index (synthetic foaming agent): 2.672
- Average index (protein-based foaming agent): 3.041

This improvement can be attributed to the greater stability and more uniform distribution of air bubbles produced by the protein-based foaming agent. A finer and more homogeneous cellular structure reduced the formation of interconnected large voids, thereby limiting the loss of compressive strength while maintaining a lower density. Among these mixtures, Mix 16 exhibited the highest mechanical efficiency.

A similar trend was observed in the second experimental series. The average performance index of mixtures produced with the protein-based foaming agent reached 4.936, compared with 4.557 for mixtures prepared with the synthetic foaming agent. These results indicate that the protein-based foaming agent generally provided superior mechanical efficiency, although the highest individual value was obtained for Mix 22, which incorporated the synthetic foaming agent.

Within the first 16 mixtures, replacing Ordinary Portland Cement (OPC) with Portland Pozzolanic Cement (PPC) resulted in a considerable improvement in both compressive strength and the performance index.

- Average compressive strength (OPC): 1.324 MPa
- Average compressive strength (PPC): 1.868 MPa
- Average performance index (OPC): 2.469
- Average performance index (PPC): 3.369

Although the mixtures containing PPC exhibited slightly higher oven-dry densities, the increase in compressive strength outweighed the increase in density, leading to an overall improvement in mechanical efficiency. This behavior can be attributed to the finer particle size of pozzolanic cement, improved particle packing, enhanced pore filling, and the development of a denser cementitious matrix. In addition, the pozzolanic reaction contributes to reducing capillary porosity and improving microstructural integrity at later curing ages.

The incorporation of 200 g/m³ of polypropylene fibers increased the average compressive strength from 1.436 MPa to 1.758 MPa, while the average oven-dry density increased from 533 to 555 kg/m³. Consequently, only a marginal improvement in the performance index was observed:

- Without fibers: 2.904
- With 200 g/m³ fibers: 2.934

These findings suggest that, at this dosage, polypropylene fibers primarily contributed to microcrack control, matrix integrity, and resistance to localized failure rather than significantly enhancing the specific mechanical performance.

In the second experimental series, increasing the polypropylene fiber dosage from 240 to 480 g/m³ unexpectedly reduced the average compressive strength from 3.033 MPa to 2.674 MPa, accompanied by a decrease in the performance index from 4.958 to 4.535. Although a slight reduction in oven-dry density was also observed, the decrease in compressive strength was more pronounced.

This behavior is likely associated with the increased viscosity of the fresh mixture, difficulties in achieving uniform fiber dispersion, local fiber agglomeration, and disturbances to foam stability. In foamed concrete, increasing fiber dosage does not necessarily improve compressive strength, as fibers primarily enhance crack resistance and post-cracking behavior. Therefore, a dosage of 240 g/m³ was considered more appropriate for maximizing the strength-to-density performance.

Among all investigated variables, increasing the cement content from 250 to 300 kg/m³ produced the most significant improvement in both compressive strength and the performance index.

- Average compressive strength (250 kg/m³): 2.199 MPa
- Average compressive strength (300 kg/m³): 3.508 MPa
- Average performance index (250 kg/m³): 3.990
- Average performance index (300 kg/m³): 5.504

Although the average oven-dry density increased from approximately 530 to 634 kg/m³, the corresponding increase in compressive strength was substantially greater. This finding indicates that the higher cement content improved the thickness and continuity of the bubble walls, thereby enhancing the strength of the cellular structure. For applications requiring higher compressive strength, a cement content of 300 kg/m³ appears to be the more suitable option, despite the associated increase in density and material cost.

The incorporation of a superplasticizer also had a pronounced positive effect. Across Mixes 17–32, the average compressive strength increased from 2.513 MPa to 3.194 MPa, while the average oven-dry density increased from 538 to 626 kg/m³. Despite this increase in density, the performance index improved from 4.470 to 5.023.

These results demonstrate that the superplasticizer enhanced the mechanical efficiency of foamed concrete by improving paste workability, reducing effective water demand, and promoting a more homogeneous mixture. Nevertheless, excessive superplasticizer dosage may destabilize the foam, promote bubble coalescence, and increase density. Therefore, determining the optimum dosage through fresh-state performance and density evaluations remains essential.

Based on the highest Specific Compressive Strength-to-Dry Density Index, Mix 22 was identified as the optimum mixture. Its composition consisted of a synthetic foaming agent, 300 kg/m³ of Portland cement, 240 g/m³ of 12-mm polypropylene fibers, and a superplasticizer. This mixture achieved a compressive strength of 4.17 MPa, an oven-dry density of 683.42 kg/m³, and the highest performance index of 6.102.

The superior performance of Mix 22 resulted from the synergistic effect of an adequate cement content, an optimum fiber dosage, and the incorporation of a superplasticizer. The increased cement content provided sufficient paste to form stronger and more continuous bubble walls, while the superplasticizer improved workability and mixture homogeneity without increasing the water content. Furthermore, the moderate fiber dosage enhanced matrix integrity without adversely affecting foam stability. Although Mixes 20 and 25 also exhibited excellent performance indices (6.004 and 5.881, respectively), Mix 22 achieved the highest compressive strength at a comparable density and was therefore identified as the optimum mix design.

4. DISCUSSION

The findings of this study demonstrate that the Specific Compressive Strength-to-Dry Density Index is an effective performance indicator for simultaneously evaluating the load-bearing capacity and lightweight efficiency of foamed concrete. Unlike compressive strength alone, this index provides a more comprehensive and realistic basis for comparing the performance of different mix designs by accounting for both mechanical strength and material density. The results revealed that foaming agent type, cement content, superplasticizer incorporation, and polypropylene fiber dosage significantly influence the performance index.

Overall, mixtures prepared with the protein-based foaming agent exhibited superior specific mechanical performance compared with those containing the synthetic foaming agent. In contrast, increasing the cement content to 300 kg/m³ produced the most pronounced improvement in both compressive strength and the performance index, highlighting the critical role of binder content in strengthening the cellular matrix. The incorporation of moderate amounts of polypropylene fibers and superplasticizer further enhanced the mechanical efficiency of foamed concrete. However, excessive dosages of these constituents adversely affected the cellular structure, resulting in reduced performance due to foam instability and disturbance of the pore network. Based on the proposed performance index, Mix 22 achieved the highest value (6.102) and exhibited the most favorable balance between compressive strength and oven-dry density, making it the optimum mixture among the investigated mix designs.

5. RECOMMENDATIONS FOR FUTURE RESEARCH

To further extend the findings of this study, future research should investigate the relationship between bubble morphology, microstructural characteristics, and the Specific Compressive Strength-to-Dry Density Index using advanced characterization techniques such as Scanning Electron Microscopy (SEM) and X-ray Computed Tomography (CT). In addition, long-term durability under various environmental exposure conditions should be evaluated to better understand the service performance of low-density foamed concrete. Further studies on alternative fiber types, supplementary cementitious materials, and emerging sustainable binders are also recommended. Moreover, the application of artificial intelligence (AI) and machine learning (ML) techniques for mix-design optimization could provide an efficient framework for developing high-performance, low-density foamed concrete with enhanced mechanical efficiency and optimized material utilization.

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