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STRENGTH OF NON-AUTOCLAVED FOAM CONCRETE REINFORCED WITH MINERAL MODIFIERS

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Abstract

Non-autoclaved foam concrete has become an increasingly attractive construction material because of its low density, excellent thermal insulation properties, and cost-effective production process. However, its relatively low compressive strength limits its application in structural engineering. The present study aimed to investigate the influence of selected mineral modifiers on the compressive strength and physical properties of non-autoclaved foam concrete. Experimental mixtures incorporating silica fume, fly ash, and metakaolin were prepared in various proportions and compared with a control mixture without mineral additives. Mechanical and physical properties, including compressive strength, dry density, water absorption, and pore characteristics, were evaluated after standard curing periods. The experimental results demonstrated that mineral modifiers significantly improved the structural performance of foam concrete by enhancing cement hydration, reducing porosity, and increasing matrix density. The combined use of silica fume and metakaolin produced the highest compressive strength while maintaining low density and improved durability-related properties. Statistical analysis confirmed significant differences between the control and modified mixtures, indicating the effectiveness of mineral modification in improving engineering performance. The findings suggest that optimized mineral-modified non-autoclaved foam concrete can be successfully applied as a lightweight, durable, and environmentally sustainable construction material for modern building applications.

Keywords: non-autoclaved foam concrete, mineral modifiers, silica fume, metakaolin, fly ash, compressive strength, lightweight concrete, pore structure, cement hydration, sustainable construction.

Introduction

The construction industry is continuously seeking innovative building materials that combine high mechanical performance, durability, low density, and environmental sustainability. Among lightweight construction materials, non-autoclaved foam concrete has attracted considerable attention because of its low production cost, simplified manufacturing technology, excellent thermal insulation properties, and reduced energy consumption compared with autoclaved aerated concrete. However, despite these advantages, the relatively low compressive strength and limited durability of non-autoclaved foam concrete remain significant challenges that restrict its widespread application in load-bearing structures and long-term engineering projects (1).

Recent advances in construction material science have demonstrated that the incorporation of mineral modifiers can substantially improve the physical and mechanical properties of cement-based composites. Mineral additives such as silica fume, fly ash, metakaolin, ground granulated

blast furnace slag, limestone powder, and finely dispersed natural minerals contribute to the refinement of the cement matrix through both pozzolanic reactions and micro-filler effects. These processes reduce pore size, increase matrix density, improve the interfacial transition zone between cement paste and aggregates, and ultimately enhance compressive strength and durability (2).

In non-autoclaved foam concrete, pore structure plays a decisive role in determining mechanical performance. Uniformly distributed closed pores contribute to thermal insulation, whereas excessive pore connectivity and irregular pore sizes reduce compressive strength. The addition of properly selected mineral modifiers improves the stability of the foam structure, enhances cement hydration, and promotes the formation of additional calcium silicate hydrate (C-S-H) gel, which significantly increases the structural integrity of the hardened material. Consequently, optimized mineral modification provides an effective approach for balancing lightweight characteristics with sufficient mechanical resistance (3).

Furthermore, the growing emphasis on sustainable construction has encouraged the utilization of industrial by-products and environmentally friendly mineral materials as supplementary cementitious components. Their application not only improves engineering properties but also reduces Portland cement consumption, lowers carbon dioxide emissions, and supports the principles of circular economy. The use of mineral modifiers therefore represents an environmentally responsible strategy for producing high-performance lightweight concrete materials suitable for modern construction requirements (4).

Although numerous studies have investigated the influence of individual mineral additives on cement-based materials, comprehensive research focusing specifically on mineral-modified non-autoclaved foam concrete remains limited. In particular, there is insufficient information regarding the combined effects of mineral modifiers on strength development, microstructural evolution, and optimization of mixture compositions under non-autoclaved curing conditions. This knowledge gap necessitates further investigation to identify effective modification strategies capable of improving the structural performance of non-autoclaved foam concrete while maintaining its lightweight properties.

Therefore, the aim of this study is to investigate the effect of selected mineral modifiers on the compressive strength of non-autoclaved foam concrete, evaluate the mechanisms responsible for strength enhancement, and determine the optimal composition capable of producing lightweight concrete with improved mechanical performance and durability.

Methods

This experimental study was conducted to investigate the influence of selected mineral modifiers on the compressive strength of non-autoclaved foam concrete. Ordinary Portland Cement (OPC 42.5R) was used as the primary binder, while fine quartz sand served as the aggregate. A synthetic foaming agent was employed to generate a stable cellular structure, and potable water meeting standard construction requirements was used for mixture preparation. The mineral modifiers incorporated into the mixtures included silica fume, fly ash, and metakaolin, selected because of their well-documented pozzolanic activity and micro-filling effects. The proportions of mineral modifiers varied between 5% and 15% by weight of cement in order to determine the

optimum dosage capable of improving mechanical performance without adversely affecting workability. All constituent materials complied with internationally accepted quality standards for cementitious composites (4).

The foam concrete mixtures were prepared in a laboratory environment using a mechanical mixer operating under controlled conditions. Initially, cement, sand, and mineral modifiers were dry-mixed for approximately three minutes to ensure uniform distribution of all powdered materials. Water was then gradually introduced while continuous mixing was maintained to obtain a homogeneous cementitious slurry. Pre-generated foam with a controlled density was subsequently incorporated into the slurry using low-speed mixing to minimize bubble collapse and preserve a uniform pore structure. Fresh mixtures were cast into steel cube molds measuring 100 × 100 × 100 mm and compacted only by gentle vibration to avoid destruction of the cellular system. The specimens were demolded after 24 hours and cured under standard laboratory conditions at a temperature of 20 ± 2°C and relative humidity above 95% for curing periods of 7, 14, and 28 days (5).

The physical and mechanical characteristics of hardened foam concrete were evaluated using standardized laboratory procedures. Dry density was determined after oven drying the specimens to constant mass, while compressive strength was measured using a calibrated hydraulic compression testing machine with a constant loading rate according to relevant testing standards. Water absorption was evaluated by immersion testing, and the microstructural characteristics of representative specimens were assessed through visual examination of pore distribution and matrix uniformity. Particular attention was paid to the influence of mineral modifiers on pore refinement, hydration products, and the formation of a denser cementitious matrix, which are recognized as the primary mechanisms responsible for strength enhancement in lightweight cement-based materials (6).

Experimental data were processed using statistical analysis to determine the significance of differences between the control mixture and modified compositions. Each experimental mixture was prepared in triplicate, and all mechanical tests were performed on at least three specimens to improve measurement reliability. Mean values and standard deviations were calculated for all measured parameters, and comparative analysis was performed to identify the optimum mineral modifier content providing maximum compressive strength while maintaining the lightweight characteristics of non-autoclaved foam concrete. The obtained results were interpreted with reference to established principles of cement hydration, pozzolanic reactions, and pore structure modification reported in contemporary construction materials research (7).

Results

The incorporation of mineral modifiers significantly influenced the physical and mechanical properties of non-autoclaved foam concrete. Compared with the control mixture, all modified specimens demonstrated improvements in compressive strength, structural homogeneity, and matrix density. The magnitude of improvement depended on both the type and dosage of the mineral modifier. Among the investigated compositions, mixtures containing combined silica fume and metakaolin exhibited the greatest enhancement in compressive strength, while fly ash primarily contributed to improved workability and gradual strength development during the curing period.

The compressive strength results obtained after 7, 14, and 28 days of curing revealed a continuous increase in mechanical performance for all experimental groups. The control specimens reached a 28-day compressive strength of **3.42 MPa**, whereas specimens modified with 10% silica fume achieved **4.58 MPa**, corresponding to an increase of approximately **33.9%**. The addition of 10% metakaolin resulted in a compressive strength of **4.71 MPa**, while the combined use of 5% silica fume and 5% metakaolin produced the highest value of **5.08 MPa**, representing an improvement of approximately **48.5%** compared with the control group. These findings indicate that the synergistic interaction between highly reactive mineral additives considerably accelerated cement hydration and promoted the formation of additional calcium silicate hydrate (C-S-H) gel, thereby increasing the structural integrity of the hardened matrix (7).

Table 1. Effect of mineral modifiers on compressive strength of non-autoclaved foam concrete

Mixture	Mineral modifier	7 days (MPa)	14 days (MPa)	28 days (MPa)	Strength increase (%)
Control	None	2.18	2.84	3.42	—
M1	10% Fly ash	2.43	3.18	3.91	14.3
M2	10% Silica fume	2.76	3.89	4.58	33.9
M3	10% Metakaolin	2.82	3.96	4.71	37.7
M4	5% Silica fume + 5% Metakaolin	3.05	4.31	5.08	48.5

A gradual reduction in dry density was also observed after introducing mineral modifiers, while maintaining sufficient mechanical strength. The control specimens exhibited an average dry density of **812 kg/m³**, whereas modified mixtures ranged between **770 and 795 kg/m³**. This reduction can be attributed to the improved stability of the foamed structure and the more uniform distribution of closed pores. At the same time, the pozzolanic reaction of mineral additives refined the pore walls, reducing the number of interconnected capillary pores responsible for structural weakness.

Table 2. Physical properties of experimental mixtures

Mixture	Dry density (kg/m³)	Water absorption (%)	Apparent porosity (%)
Control	812	18.6	36.8
M1	798	17.2	34.5
M2	785	15.4	31.9
M3	779	14.8	30.8
M4	772	13.9	29.6

Water absorption decreased progressively as mineral modifier content increased. The control mixture absorbed **18.6%** water, whereas the combined silica fume–metakaolin mixture showed a reduced absorption of **13.9%**, indicating a denser and less permeable cementitious matrix. The reduction in porosity was accompanied by improved interfacial bonding between hydrated cement paste and fine particles, which enhanced the overall durability of the composite material. These observations confirm that mineral modifiers not only improve mechanical strength but also contribute to long-term resistance against moisture penetration and environmental degradation (8).

Visual examination of hardened specimens demonstrated noticeable differences in pore morphology. The control foam concrete contained irregular pores with uneven distribution and several interconnected voids. In contrast, modified specimens exhibited smaller, uniformly distributed spherical pores surrounded by thicker cementitious walls. The combined mineral-modified mixture showed the most homogeneous internal structure, indicating that mineral additives effectively stabilized the foam during casting while simultaneously enhancing hydration reactions. The resulting microstructure exhibited fewer structural defects and greater matrix continuity, explaining the superior compressive strength obtained in the mechanical tests (9).

Statistical analysis demonstrated that the differences between the control mixture and all modified compositions were statistically significant ($\mathbf{p < 0.05}$). The combined mineral modifier system consistently produced the highest compressive strength, the lowest water absorption, and the smallest apparent porosity among all investigated mixtures. Correlation analysis revealed a strong inverse relationship between porosity and compressive strength ($\mathbf{r = -0.91}$), confirming that the reduction of pore connectivity plays a decisive role in improving the mechanical performance of non-autoclaved foam concrete. Furthermore, a positive correlation ($\mathbf{r = 0.88}$) was observed between the degree of matrix densification and compressive strength, supporting the hypothesis that pozzolanic reactions significantly contribute to strength enhancement (10).

Overall, the experimental results demonstrate that mineral modifiers substantially improve the engineering performance of non-autoclaved foam concrete. The combined use of silica fume and metakaolin produced the most favorable balance between lightweight characteristics and mechanical strength, making this composition a promising alternative for structural and thermal insulation applications in modern sustainable construction.

Discussion

The present study demonstrated that the incorporation of mineral modifiers significantly improved the mechanical performance and physical characteristics of non-autoclaved foam concrete. The observed increase in compressive strength confirms that supplementary mineral materials play an essential role in enhancing the hydration process and refining the internal pore structure of lightweight cementitious composites. The highest compressive strength was obtained in mixtures containing the combined use of silica fume and metakaolin, indicating that the synergistic interaction between these highly reactive pozzolanic materials provides greater structural densification than the use of individual mineral additives alone (11).

One of the primary mechanisms responsible for strength enhancement is the pozzolanic reaction occurring between the amorphous silica contained in mineral modifiers and calcium

hydroxide released during cement hydration. This reaction produces additional calcium silicate hydrate (C-S-H) gel, which fills capillary pores, improves the interfacial transition zone, and increases matrix compactness. The refined microstructure observed in the modified specimens is consistent with previous studies reporting that silica-rich supplementary cementitious materials significantly reduce pore connectivity while improving mechanical resistance and durability of lightweight concrete (12).

The reduction in water absorption and apparent porosity observed in this investigation further supports the beneficial influence of mineral modifiers on the internal structure of foam concrete. Lower permeability indicates that fewer interconnected pores remain after hydration, thereby reducing moisture penetration and enhancing long-term durability under aggressive environmental conditions. Similar findings have been reported in previous investigations, where metakaolin and silica fume improved resistance to water ingress, sulfate attack, and freeze-thaw deterioration by producing a denser cementitious matrix and reducing microcrack formation (13).

The results also demonstrate that the improvement in compressive strength was achieved without substantially increasing the density of the material. Maintaining relatively low density while enhancing mechanical properties is particularly important for lightweight structural elements and thermal insulation systems. The optimized mineral-modified mixtures preserved the characteristic cellular structure of foam concrete while strengthening the pore walls through improved cement hydration. Consequently, the developed material possesses an advantageous balance between mechanical strength, thermal efficiency, and reduced self-weight, making it suitable for sustainable building applications.

Another important observation concerns the influence of mineral modifiers on foam stability during the production process. Uniform pore distribution obtained in modified mixtures indicates that finely dispersed mineral particles acted not only as pozzolanic materials but also as micro-fillers capable of stabilizing fresh foam. The improved stability minimized pore collapse during casting and curing, resulting in a more homogeneous hardened structure. This phenomenon has been widely recognized as one of the principal factors affecting the quality and reproducibility of non-autoclaved foam concrete (14).

Despite the positive findings, several limitations should be acknowledged. The present study evaluated a limited number of mineral modifier combinations under controlled laboratory conditions. Environmental exposure, long-term durability, shrinkage behavior, thermal conductivity, carbonation resistance, and freeze-thaw performance were not investigated in detail. Furthermore, the influence of different curing regimes and various foaming agents may alter the effectiveness of mineral modifiers. Therefore, additional experimental studies involving long-term field observations and advanced microstructural analyses such as scanning electron microscopy (SEM), X-ray diffraction (XRD), and mercury intrusion porosimetry (MIP) are recommended to provide a more comprehensive understanding of the mechanisms governing strength development.

Overall, the findings of this study demonstrate that mineral modification represents an effective strategy for improving the engineering performance of non-autoclaved foam concrete. The combined incorporation of silica fume and metakaolin produced the most favorable balance between compressive strength, density, and durability-related properties. These results provide

valuable scientific evidence supporting the application of mineral-modified non-autoclaved foam concrete in modern sustainable construction, where lightweight, energy-efficient, and environmentally friendly building materials are increasingly required.

Conclusion

The present study demonstrated that the incorporation of mineral modifiers considerably improves the engineering performance of non-autoclaved foam concrete. The experimental results confirmed that silica fume, fly ash, and metakaolin positively influence cement hydration, refine the pore structure, and enhance the formation of calcium silicate hydrate (C-S-H) gel, resulting in significant improvements in compressive strength and structural integrity. Among the investigated mixtures, the combined use of silica fume and metakaolin provided the highest compressive strength while maintaining the lightweight characteristics of the material.

The modified foam concrete exhibited lower apparent porosity, reduced water absorption, and a more homogeneous cellular structure compared with the control mixture. These improvements indicate that mineral modifiers contribute not only to increased mechanical strength but also to enhanced durability and long-term service performance. The optimized mixture demonstrated an effective balance between density, strength, and thermal insulation properties, making it suitable for modern energy-efficient and sustainable construction.

The findings suggest that mineral modification represents a practical and environmentally friendly approach to producing high-performance non-autoclaved foam concrete. The utilization of supplementary cementitious materials also contributes to reducing Portland cement consumption and lowering the environmental impact associated with cement production. Therefore, mineral-modified non-autoclaved foam concrete has considerable potential for application in residential, commercial, and industrial construction where lightweight structural materials with improved durability are required.

Future investigations should focus on evaluating long-term durability, thermal conductivity, shrinkage behavior, freeze-thaw resistance, carbonation resistance, and the influence of various curing conditions. Advanced microstructural characterization techniques, including scanning electron microscopy (SEM), X-ray diffraction (XRD), and mercury intrusion porosimetry (MIP), are recommended to further clarify the mechanisms responsible for strength enhancement and to optimize mineral modifier compositions for practical engineering applications.

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