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Material-Related Carbon and Functional Performance of D800 Non-Autoclaved Foam Concrete Modified with Fly Ash and Microsilica

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Abstract

The present study evaluates the environmental and functional performance of D800 non-autoclaved foam concrete in which Portland cement was partially replaced by fly ash and microsilica. A modified binder containing 15% fly ash and 5% microsilica was selected through preliminary screening and compared with a reference composition. The experimental program included density, compressive and flexural strength, thermal conductivity, and SEM observations. Environmental performance was assessed by a comparative material-related global warming potential (GWP) calculation using EPD- and LCI-based emission factors, together with performance-normalized carbon intensity and sensitivity analysis for the environmental burdens assigned to the secondary mineral components. The modified mixture reduced Portland-cement consumption by 20% and incorporated 83 kg/m³ of secondary industrial materials. Its 28-day compressive strength increased from 3.00 to 4.20 MPa, while thermal conductivity decreased from 0.270 to 0.221 W/(m·K). Material-related GWP declined from 355.16 to 311.09 kg CO_2-eq/m³, corresponding to a reduction of 12.4%, whereas carbon intensity decreased by 37.4%. Under a conservative sensitivity scenario, the modified mixture still maintained lower GWP and carbon intensity than the reference. These findings show that the proposed modification strategy improves resource efficiency without compromising functional performance. Overall, the optimized foam-concrete system incorporating fly ash and microsilica as partial cement replacements reduced cement demand and material-related carbon burden while maintaining improved mechanical and thermal performance relative to the reference composition.

Keywords: Non-autoclaved foam concrete; fly ash; microsilica; material-related GWP; carbon intensity; secondary industrial materials; thermal conductivity; low-carbon construction.

Introduction

The decarbonization of construction materials has become an important component of climate-change mitigation. Buildings and construction are responsible for a substantial share of global greenhouse-gas emissions and material consumption, while cement production remains one of the major carbon-intensive processes in the sector[1,2]. Reducing clinker-containing cement consumption and increasing the use of suitable secondary industrial materials are therefore important strategies for lowering the environmental burden of cement-based products.

Foam concrete is a lightweight cementitious material characterized by low density and comparatively low thermal conductivity due to its cellular structure[3,4]. These properties make it attractive for building-envelope applications, where reduced heat transfer may contribute to lower heating and cooling demand during operation[5]. At the same time, the high pore volume that provides thermal-insulation benefits may adversely affect strength and structural stability.

Therefore, lowering cement consumption in foam concrete should not be considered environmentally advantageous unless adequate functional performance is maintained.

Fly ash and microsilica are widely investigated as supplementary cementitious materials because they can partially replace Portland cement while modifying the structure and properties of cementitious composites. Previous studies have shown that both materials can influence density, strength, water absorption, pore structure and thermal conductivity of foam concrete[6,7]. More recent research has also demonstrated the potential of combined fly-ash–silica-fume systems to balance mechanical and thermal performance in lightweight foam concrete[8].

However, most previous investigations have focused primarily on mix optimization and physical-mechanical properties. Environmental benefits are often discussed mainly in terms of cement replacement or industrial by-product utilization, although secondary materials themselves may carry non-zero environmental burdens associated with processing and supply[9,10].

In addition, comparison based only on GWP per cubic metre may be insufficient when the mechanical performance of the mixtures differs substantially. Performance-normalized indicators can therefore provide a more meaningful measure of environmental efficiency[11].

Accordingly, comparatively limited attention has been given to the integrated environmental and functional assessment of low-density non-autoclaved foam concrete containing fly ash and microsilica, particularly when material-related GWP, secondary-material utilization, thermal performance, carbon efficiency and uncertainty in the environmental burdens of the secondary components are considered together.

The aim of the present study was therefore to develop and environmentally evaluate a D800 non-autoclaved foam concrete containing fly ash and microsilica as partial replacements for Portland cement. The study included binder-level screening, mechanical and thermal characterization, SEM observations, material-related GWP assessment based on EPD and LCI data, performance-normalized carbon-intensity analysis and sensitivity analysis using more conservative GWP factors for the secondary mineral components.

Materials and Methods

Materials: i. Cement: CEM II/A-K 42.5 H (containing 10–20% limestone filler), ii. Quartz sand: particle size $\leq 0.315\ mm$, iii. Microsilica (MS, Figure-1 (a)): industrial by-product from JSC Uzmetkombinat (Uzbekistan), SiO_2 content 90–92%, bulk density 0.50g/cm³, true density 1.50 g/cm³, and specific surface area 4440cm²/g. iv. Fly ash (FA, Figure-1 (b)): Novo-Angren TPP lignite fly ash, LOI 1.2%, bulk density 0.63g/cm³, true density 2.50g/cm³, specific surface area 7941cm²/g. v. Superplasticizer: Master Glenium ACE, based on polycarboxylate ether, vi. Synthetic liquid foaming agent: PB-2000, based on anionic surfactants, vii. Water: tap water.



(a) (b)

Figure-1: Secondary mineral materials used in the study: (a) microsilica; (b) fly ash.

Experimental design: The experimental program consisted of two consecutive stages. In the first stage, fly ash and microsilica were evaluated separately as partial cement-replacement materials in order to determine rational replacement levels based on their effects on water demand and 28-day compressive strength. Each mineral component was investigated at replacement levels of 5, 10, 15 and 20% by mass of the total cementitious component (Table-1).

Based on the combined assessment of water demand and compressive strength, 5% microsilica and 15% fly ash were selected as the rational replacement levels. The purpose of the second stage was not to re-optimize the individual mineral components, but to verify whether the selected replacement levels could be effectively implemented in a practical D800 non-autoclaved foam-concrete system. Accordingly, the selected contents were combined, resulting in a total Portland-cement replacement of 20%, and the resulting modified foam concrete was compared with a reference D800 composition containing Portland cement as the sole binder.

The water content of each composition was adjusted to obtain comparable consistency. Consistency was evaluated using a Vicat apparatus, and the required consistency was considered achieved when the plunger stopped 5–7mm above the base plate.

Table-1: Binder compositions used for preliminary screening.

Mix	Cement, g	Mineral component, g	Replacement, %	Water, g
Control	400	–	0	120
MS5	380	20	5	126.5
MS10	360	40	10	142
MS15	340	60	15	146
MS20	320	80	20	155
FA5	380	20	5	130
FA10	360	40	10	138
FA15	340	60	15	144
FA20	320	80	20	150

The relatively high specific surface areas of the mineral components increased the water demand of the cementitious system. Therefore, a polycarboxylate-based superplasticizer was incorporated into the modified foam-concrete mixture as a technological measure to control the required mixing-water content while maintaining suitable workability and stability of the preformed foam system. Accordingly, the second-stage comparison was intended to evaluate the performance of the complete optimized foam-concrete system under practical mixture-design conditions, rather than to attribute the observed changes in foam-concrete properties to any single constituent.

Foam-concrete mix composition and specimen preparation: Based on the preliminary binder screening, a modified D800 non-autoclaved foam-concrete composition was prepared using the selected replacement levels of 15% fly ash and 5% microsilica.

A reference mixture (R2) containing Portland cement as the sole binder was produced for comparison. In both mixtures, the total binder content was maintained at 415kg/m³ and the sand content at 312kg/m³. Thus, the modified mixture differed from the reference primarily by the replacement of 20% of Portland cement with two secondary industrial mineral components.

In the modified composition (M2), the binder consisted of 332 kg/m³ Portland cement, 62.25kg/m³ fly ash and 20.75kg/m³ microsilica, corresponding to 80, 15 and 5% of the total binder mass, respectively. A polycarboxylate-based superplasticizer was incorporated at 4.15kg/m³, equivalent to 1% of the total binder mass. The use of the superplasticizer reduced the amount of mixing water required to obtain suitable workability, from 327.15L/m³ in the reference mixture to 225.37L/m³ in the modified mixture. Target dry density was 800kg/m^3.

Table-2: Mix proportions of the reference and modified D800 non-autoclaved foam concrete.

Component	R2 reference	M2 modified
Cement, kg/m³	415.00	332.00
Quartz sand, kg/m³	312.00	312.00
Fly ash, kg/m³	–	62.25
Microsilica, kg/m³	–	20.75
Mixing water for cementitious slurry, L/m³	327.15	225.37
PCE superplasticizer, kg/m³	–	4.15
Foaming-agent concentrate, kg/m³	1.03	1.06
Total binder, kg/m³	415.00	415.00
Cement replacement, %	0	20

Note: The water contents reported in Table-2 refer only to the water used for preparation of the cementitious slurry and do not include the water used for preparation of the preformed foam solution.

The total amount of solid mineral material excluding the foaming agent was kept constant between the two compositions. The water-to-solid ratio decreased from approximately 0.45 for R2 to 0.31 for M2, mainly due to the use of the polycarboxylate superplasticizer.

Both mixtures were prepared under identical laboratory conditions. For the modified mixture, Portland cement, fly ash and microsilica were first dry-blended until a homogeneous powder mixture was obtained. Approximately 70% of the required mixing water was then added and the cementitious slurry was mixed until homogeneous.

The polycarboxylate-based superplasticizer was separately dispersed in the remaining 30% of the mixing water and subsequently introduced into the slurry. The reference mixture was prepared according to the same general procedure, except that fly ash, microsilica and superplasticizer were not incorporated.

The preformed foam was produced using a laboratory foam generator. The foaming solution contained foaming-agent concentrate at 5% of the mass of water used for foam preparation. The density of the generated technical foam was maintained within 60–70kg/m³. Foam stability was evaluated using the drainage criterion and was found to be satisfactory for incorporation into the cementitious mixture.

The prepared foam was gradually and continuously introduced into the slurry while the mixture was simultaneously mixed. Foam addition was controlled by the fresh density of the cellular mixture, which was approximately 820kg/m³ for the D800 composition. After a homogeneous cellular mixture was obtained, it was immediately cast into the moulds. Only light manual tapping of the moulds was applied to facilitate filling while minimizing disturbance of the cellular structure. The specimens were demoulded after 48h. Separate sets of three specimens were prepared for each testing age. After demoulding, the specimens were cured under identical humid conditions and tested for compressive strength at 3, 7 and 28 days.

The modified binder was designed to reduce Portland-cement consumption through the combined use of two secondary industrial mineral components, fly ash and microsilica. Fly ash provides a fine aluminosilicate fraction that contributes to particle packing and later-age pozzolanic activity, while microsilica, owing to its high SiO_2 content and high fineness, enhances microfilling and matrix densification. Their complementary action was intended to preserve the integrity of the foam-concrete pore walls despite a 20% reduction in cement content. Because the increased specific surface area of the blended binder raised water demand, a polycarboxylate-based superplasticizer was used to improve particle dispersion and reduce the required mixing water.

The resulting composition therefore combined cement reduction, utilization of industrial by-products and maintenance of structural performance, which formed the basis for the subsequent embodied-carbon assessment.

Testing and Curing Conditions: For the preliminary binder-level screening, cement compositions containing different amounts of fly ash (FA) and microsilica (MS) were prepared separately. Compressive strength was determined using 20 × 20 × 20 mm cubic specimens. Six specimens were prepared for each composition and cured under identical laboratory conditions for 28 days.

The 28-day compressive-strength results, together with the water demand required to achieve the specified Vicat consistency, were used to identify the rational replacement levels of fly ash and microsilica for subsequent application in the D800 foam-concrete system. The reported compressive-strength value represents the arithmetic mean of six specimens.

For the D800 non-autoclaved foam concrete, 100 × 100 × 100 mm cubic specimens were prepared for compressive-strength testing (Figure-2). After demolding, the specimens were cured under standard conditions in a humidity chamber at a temperature of (20±2)°C and a relative humidity of at least 95%. Compressive strength was determined at 3, 7, and 28 days in accordance with GOST 10180–2012. For each composition and testing age, three specimens were tested, and the reported value represents the arithmetic mean of the individual measurements.

Flexural strength was determined at 28 days using three prismatic specimens with dimensions of 40 × 40 × 160 mm for each composition. The reported flexural-strength value represents the arithmetic mean of the three specimens.

The average density of the hardened foam concrete was determined in accordance with GOST 12730.1–2020. Before density determination, the specimens were conditioned using the same drying procedure adopted throughout the experimental program. After removal of excess surface moisture, the specimens were weighed, their geometric dimensions were measured, and the average density was calculated from the specimen mass and volume.

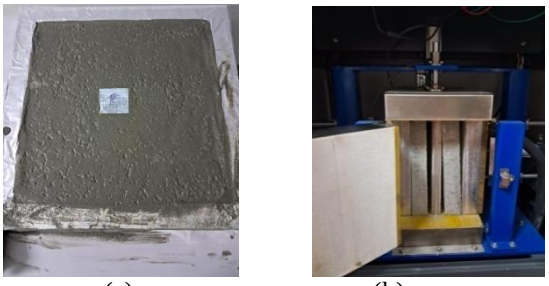


(a) (b)

Figure-2: D800 non-autoclaved foam-concrete specimens: (a) freshly molded specimens; (b) hardened specimens prepared for physical and mechanical testing.

For thermal-conductivity testing, plate specimens with dimensions of 300 × 300 × 40 mm were prepared (Figure-3). After 28 days of curing, the specimens were dried to constant mass using the same conditioning procedure. Thermal conductivity was then determined under steady-state conditions using an XND-2-3030C thermal-conductivity apparatus in accordance with GOST 7076–99.

Microstructural observations were carried out on selected control and modified specimens after 28 days of curing using a JEOL JSM-IT510 scanning electron microscope (JEOL Ltd., Japan) equipped with secondary-electron and backscattered-electron detectors. The SEM images were used for comparative evaluation of pore morphology, inter-pore wall structure, matrix compactness, and visible structural defects in the reference and modified foam-concrete specimens.



(a) (b)

Figure-3: Experimental determination of the thermal conductivity of D800 non-autoclaved foam-concrete specimens.

Environmental Assessment: The environmental assessment was conducted as a comparative partial product carbon-footprint study following the principles and requirements of ISO 14040, ISO 14044 and ISO 14067[12-14]. Construction-product-specific methodological principles were additionally considered in accordance with ISO 21930 and EN 15804+A2[15,16]. The assessment addressed the climate-change impact category only and therefore should not be interpreted as a complete multi-category life-cycle assessment.

The functional unit was defined as 1 m³ of hardened D800 non-autoclaved foam concrete. The system boundary was limited to the upstream production of the constituent materials used in the reference and modified mixtures. Transportation to the foam-concrete production site, manufacturing energy, construction, use and end-of-life stages were excluded and are therefore outside the calculated carbon footprint.

The material inventory comprised Portland cement, quartz sand, fly ash, microsilica, water, polycarboxylate superplasticizer and foaming agent. Wherever available, greenhouse-gas emission factors were obtained from product-specific or sector-average EPDs prepared according to ISO 21930 and/or EN 15804+A2[15-23]. Where suitable EPD data were unavailable, peer-reviewed life-cycle inventory data consistent with the defined system boundary were used[17]. All emission factors were expressed on a common basis of kg CO_2-eq/kg of material before being applied in the calculations.

In the absence of a product-specific EPD for the cement used in the experiments, a verified EPD for CEM II/A-LL 42.5N with a comparable cement class and limestone-containing composition was adopted as a proxy dataset[18].

Because product-specific environmental data were not available for all materials used in the experiments, some emission factors were represented by verified proxy EPD datasets. Therefore, the calculated values should be interpreted as a comparative material-related carbon assessment rather than as a product-specific carbon footprint representative of production conditions in Uzbekistan.

Following the inventory-based life-cycle assessment framework defined in ISO 14044 and ISO 14067[13,14], the material-related global warming potential was calculated as:

$$GWP_{mat} = \sum_{i=1}^{n} m_i EF_i \,, \quad (1)$$

Where: m_i is the quantity of constituent i used per functional unit (kg/m³) and EF_i is its corresponding GWP factor (kg CO_2-eq/kg). The total result was expressed as kg CO_2-eq/m³.

The emission-factor inventory used in the calculation was structured as follows:

Environmental burdens assigned to fly ash and microsilica were treated in accordance with the allocation principles of ISO 14044. Because both materials originate as secondary outputs of industrial processes, a zero environmental burden was not assumed automatically. Instead, published EPD- or literature-based GWP factors reflecting alternative allocation assumptions were considered in a sensitivity analysis. A base-case scenario and a more conservative sensitivity scenario were used to evaluate whether the environmental advantage of the modified mixture remained consistent under different burden-allocation assumptions.

The relative reduction in material-related GWP of the modified mixture compared with the reference mixture was calculated as:

$$GWP_R = \frac{GWP_{ref} - GWP_{mod}}{GWP_{ref}} \times 100, \quad (2)$$

where GWP_{ref} and GWP_{mod} are the material-related GWP values of the reference and modified mixtures, respectively.

The reduction in Portland-cement consumption was calculated as:

$$CR = \frac{C_{ref} - C_{mod}}{C_{ref}} \times 100, \quad (3)$$

Where: C_{ref} and C_{mod} are the cement contents of the reference and modified mixtures, respectively. In the present study, the cement content was reduced from 415 to 332 kg/m³, corresponding to a 20% reduction.

The utilization of secondary industrial mineral materials was expressed as the combined mass of fly ash and microsilica incorporated per cubic metre of foam concrete:

$$SMU = m_{FA} + m_{MS}, \quad (4)$$

where m_{FA} and m_{MS} are the contents of fly ash and microsilica, respectively. For the modified composition, the total secondary-material utilization was 83.0 kg/m³.

To relate environmental burden to mechanical performance, a performance-normalized carbon-intensity indicator was calculated following the approach proposed by Damineli et al.[11]:

$$CI = \frac{GWP_{mat}}{f_{c,28}}, \quad (5)$$

where $f_{c,28}$ is the mean 28-day compressive strength of the corresponding foam-concrete composition (MPa). The carbon-intensity indicator was expressed as kg CO_2-eq/(m³·MPa). A lower value indicates a lower material-related carbon burden per unit of compressive performance.

The potential environmental benefit associated with the thermal-insulation performance of foam concrete was considered separately in the discussion. Because whole-building energy consumption was not modelled in the present study, possible reductions in operational heating or cooling demand were not included in the calculated carbon-footprint values.

Table-3: GWP emission factors and environmental data sources used in the material-related carbon assessment.

Material	R2 / FA15–MS5, kg/m³	GWP factor, kg CO_2-eq/kg	References	Registration	Boundary
Portland cement	415 / 332	0.835	18	EPD-IES-0026521:001	A1–A3
Quartz sand	312 / 312	0.02316	19	EPD-IES-0030293:001	A1–A3
Fly ash	0 / 62.25	0.0924	20	EPD-IES-0032541:001	A1–A3
Microsilica	0 / 20.75	0.599	21	EPD-IES-0032939:002	A1–A3
Mixing water	327.15 / 225.37	0.000020	17	—	Upstream supply
PCE super plasticizer	0 / 4.15	1.69	22	EPD-IES-0025863:002	A1–A3
Foaming agent	1.03 / 1.06	1.36	23	EPD-IES-0010978:001	A1–A3

Results and Discussion

Physical and Mechanical Properties: A preliminary binder-level screening was carried out to identify suitable replacement levels of microsilica and fly ash before their combined incorporation into D800 non-autoclaved foam concrete. In this stage, cement was separately replaced by microsilica or fly ash at levels of 5, 10, 15 and 20%, and the 28-day compressive strength of the cementitious matrix was determined. The results are presented in Figure-4.

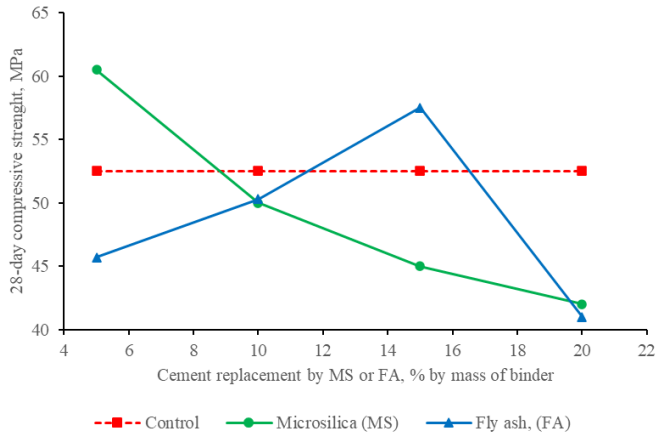


Figure-4: Effect of microsilica and fly ash replacement level on the 28-day compressive strength of the cementitious matrix

As shown in Figure-4, the two mineral components exhibited different optimum replacement levels. In the microsilica series, the highest 28-day compressive strength was obtained at 5% replacement, where the strength increased from 52.3 MPa for the control mixture to 60.5 MPa. A further increase in microsilica content resulted in a progressive decline in compressive strength.

In the fly-ash series, the highest strength was achieved at 15% replacement, reaching 57.5 MPa, whereas a further increase to 20% caused a marked reduction in strength. At the same time, increasing dosages of both mineral components were associated with higher water demand, which justified the subsequent use of a polycarboxylate-based superplasticizer in the foam-concrete mixtures. Based on the screening results, 5% microsilica and 15% fly ash were selected for combined use in the modified D800 composition.

The selected replacement levels were subsequently applied in the macro-scale non-autoclaved foam-concrete system. The development of compressive strength of the reference mixture (R2) and the modified mixture (FA15–MS5) is shown in Figure-5. Despite a 20% reduction in Portland-cement content, the modified composition showed higher compressive strength at all investigated curing ages.

The observed improvement is consistent with previous studies reporting beneficial effects of fly ash and silica-fume-type additions on the hardened properties and microstructure of foam concrete. Earlier investigations have shown that these supplementary mineral components can modify particle packing, hydration products and the structure of the inter-pore walls, thereby influencing the mechanical performance of cellular cementitious materials[6-8]. In the present study, the combined use of 15% fly ash and 5% microsilica within the optimized foam-concrete system provided higher compressive strength without a substantial increase in average density, indicating that the performance improvement was associated with modification of the cementitious matrix rather than simple densification.

This improvement should be interpreted as the performance of the complete optimized modification strategy, which combined the selected fly-ash and microsilica replacement levels with water-demand control using a polycarboxylate-based superplasticizer, rather than as the isolated effect of fly ash or microsilica alone. At 3 days, the compressive strength increased from 1.19 MPa for the reference mixture to 1.55 MPa for the modified mixture. At 7 days, the corresponding values were 1.93 MPa and 3.45 MPa, while at 28 days the strength increased from 3.00 MPa to 4.20 MPa. Thus, the 28-day compressive strength of the modified foam concrete was approximately 40% higher than that of the reference composition.

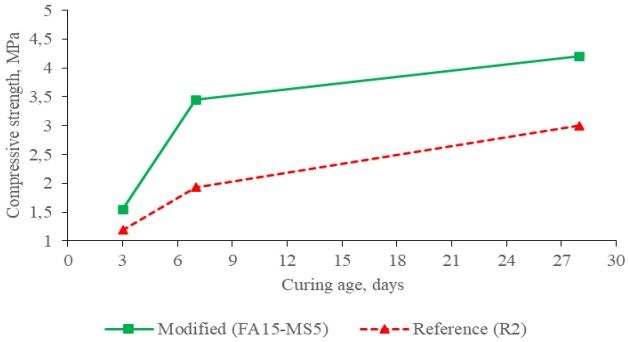
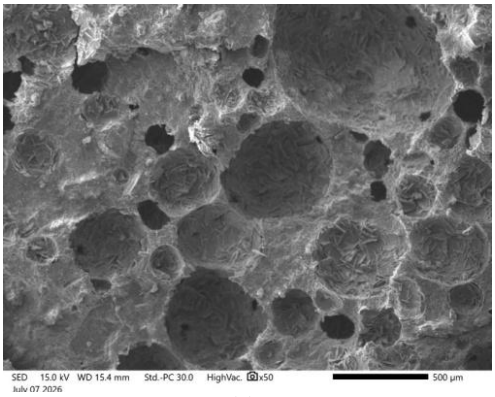
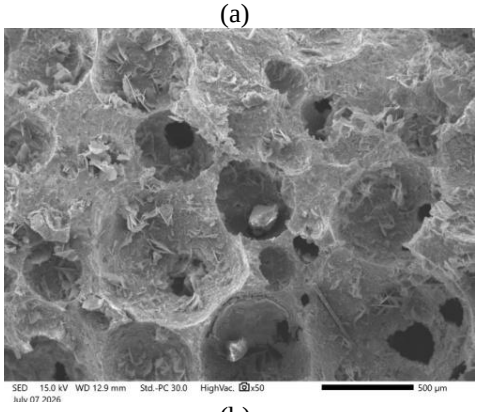


Figure-5: Development of compressive strength of the reference (R2) and modified (FA15–MS5) D800 non-autoclaved foam concretes.

The average densities of the two D800 mixtures remained very similar, amounting to 808 kg/m³ for the reference composition and 815 kg/m³ for the modified composition. This indicates that the improvement in compressive strength was not achieved through a substantial increase in density. In addition, the 28-day flexural strength increased from 0.31 MPa for the reference mixture to 0.52 MPa for the modified composition, further confirming the beneficial influence of the selected mineral replacement strategy on the structural performance of the foam concrete. The mechanical results were further supported by microstructural observations (Figure-6).



(a)



(b)

Figure-6: SEM images of the reference (a) and modified (b) foam-concrete matrices after 28 days of curing (×50 magnification).

Compared with the reference composition, the modified matrix appeared more compact and homogeneous, with more continuous inter-pore walls and fewer visible structural defects. These qualitative microstructural observations are consistent with the higher compressive strength of the FA15–MS5 composition and indicate that partial cement replacement by fly ash and microsilica did not adversely affect the integrity of the hardened foam-concrete matrix.

The thermal conductivity of the reference D800 foam concrete (R2) was 0.270 W/(m·K), whereas the modified FA15–MS5 composition exhibited a lower value of 0.221 W/(m·K). Thus, the thermal conductivity decreased by approximately 18.1%. Considering that both compositions remained within the D800 density class, this reduction indicates improved thermal-insulation performance of the modified foam concrete. The lower thermal conductivity may reduce heat transfer through building-envelope elements and therefore provides an additional potential environmental benefit during the service stage. However, the associated reduction in operational energy consumption was not quantified in the present study. This trend is also consistent with the broader literature on lightweight foam concrete, in which thermal performance is closely related to density, pore structure and the characteristics of the solid matrix[3–5].

Overall, the FA15–MS5 composition combined a 20% reduction in Portland-cement content with increased mechanical strength and an 18.1% reduction in thermal conductivity, providing the experimental basis for the environmental assessment presented in the following sections.

Material-Related GWP and Resource Efficiency: Using the calculation procedure described in the Environmental Assessment sectionand Eq. (1), the material-related global warming potential (GWP) was determined for the reference (R2) and modified (FA15–MS5) D800 non-autoclaved foam-concrete mixtures. The calculated contributions of the individual constituents and the total GWP values are presented in Table-4 and Figure-7.

Table-4. Material-related GWP contributions of the reference and modified D800 foam-concrete mixtures

Component	R2, kg CO_2-eq/m³	FA15–MS5, kg CO_2-eq/m³
Portland cement	346.53	277.22
Quartz sand	7.23	7.23
Fly ash	0	5.75
Microsilica	0	12.43
Mixing water	0.007	0.005
PCE superplasticizer	0	7.01
Foaming agent	1.40	1.44
Total	355.16	311.09

As shown in Table-4, Portland cement was the dominant source of material-related GWP in both compositions. In the reference mixture, cement contributed 346.53 kg CO_2-eq/m³, accounting for approximately 97.6% of the total GWP of 355.16 kg CO_2-eq/m³. The contribution of quartz sand was 7.23 kg CO_2-eq/m³, while the impacts associated with mixing water and the foaming agent were comparatively small.

In the modified FA15–MS5 composition, the Portland-cement content was reduced from 415 to 332 kg/m³, corresponding to a reduction of 83 kg/m³, or 20%. The removed cement was replaced by 62.25 kg/m³ of fly ash and 20.75 kg/m³ of microsilica, resulting in the incorporation of 83 kg/m³ of secondary industrial mineral materials.

The reduction in cement content decreased the cement-related GWP from 346.53 to 277.22 kg CO_2-eq/m³, corresponding to an avoided cement-related burden of approximately 69.31 kg CO_2-eq/m³. However, the replacement materials and the chemical admixture also introduced non-zero upstream environmental

burdens. Fly ash contributed 5.75 kg CO_2-eq/m³, microsilica 12.43 kg CO_2-eq/m³, and the PCE superplasticizer 7.01 kg CO_2-eq/m³ to the modified composition.

The component-wise distribution of these environmental burdens is illustrated in Figure-7. Despite the additional contributions associated with the mineral additions and superplasticizer, Portland cement remained the principal contributor to the modified mixture, accounting for approximately 89.1% of its total material-related GWP.

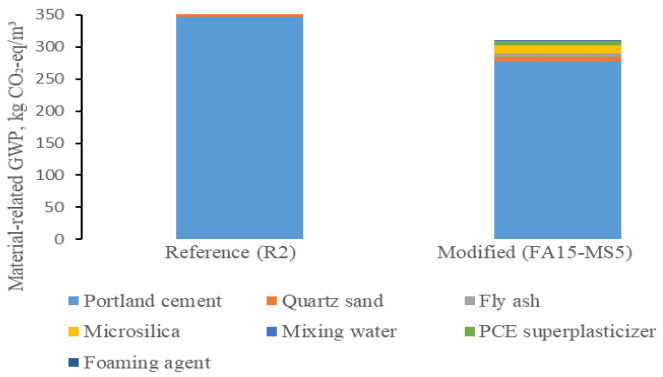


Figure-7: Component-wise material-related GWP of the reference (R2) and modified (FA15–MS5) D800 non-autoclaved foam-concrete mixtures.

Taking all constituent materials into account, the total material-related GWP decreased from 355.16 kg CO_2-eq/m³ for the reference mixture to 311.09 kg CO_2-eq/m³ for the FA15–MS5 composition. This corresponds to an absolute reduction of 44.07 kg CO_2-eq/m³ and a relative reduction of approximately 12.4%.

The difference between the 20% reduction in Portland-cement content and the 12.4% reduction in material-related GWP is environmentally significant. It demonstrates that the carbon benefit of cement substitution cannot be estimated directly from the cement-replacement percentage, because fly ash, microsilica and the superplasticizer also carry upstream environmental burdens[20-22]. The use of component-specific EPD-based GWP factors therefore provides a more transparent and conservative assessment than an approach in which secondary industrial materials are assumed to have zero environmental impact.

From a resource-efficiency perspective, the modified composition provided two simultaneous benefits: 83 kg/m³ of Portland cement was avoided, while an equivalent mass of secondary industrial mineral materials was incorporated into the binder system. As demonstrated in the Physical and Mechanical Properties section, this reduction in cement consumption was achieved without loss of functional performance and was accompanied by an increase in 28-day compressive strength. Thus, the FA15–MS5 composition combined reduced demand for clinker-containing cement, utilization of secondary industrial resources and a lower material-related carbon burden.

Carbon–Strength Efficiency and Sensitivity Analysis: To evaluate the environmental efficiency of the mixtures in relation to mechanical performance, the performance-normalized carbon-intensity indicator was calculated according to Equatio (5), following the eco-efficiency approach described in the Environmental Assessment section[11].

For the reference mixture (R2), the carbon-intensity value was 118.39 kg CO_2-eq/(m³·MPa), whereas the corresponding value for the modified FA15–MS5 composition was 74.07 kg CO_2-eq/(m³·MPa). Thus, the modified composition reduced the material-related carbon burden per unit of 28-day compressive strength by approximately 37.4%. This improvement was considerably greater than the 12.4% reduction in material-related GWP per cubic metre reported in the Material-Related GWP and Resource Efficiency section because the modified mixture simultaneously exhibited a lower GWP and a higher 28-day compressive strength.

Table-5: Carbon–strength efficiency and sensitivity-analysis results

Indicator	Reference R2	FA15–MS5, base case	FA15–MS5, conservative scenario
28-day compressive strength, MPa	3.00	4.20	4.20
Material-related GWP, kg CO_2-eq/m³	355.16	311.09	315.46
GWP reduction relative to R2, %	—	12.4	11.2
Carbon intensity, kg CO_2-eq/(m³·MPa)	118.39	74.07	75.11
Carbon-intensity reduction, %	—	37.4	36.6

Because fly ash and microsilica are secondary outputs of other industrial processes, the environmental burdens attributed to these materials may vary depending on allocation assumptions, processing conditions and the background datasets used. Therefore, a conservative sensitivity scenario was introduced to examine whether the environmental advantage of the FA15–MS5 composition remained robust when higher GWP factors were assigned to the two secondary mineral components.

For fly ash, the base-case factor of 0.0924 kg CO_2-eq/kg was replaced by a more conservative value of 0.148 kg CO_2-eq/kg, corresponding to the background burden reported for hard-coal fly ash within an EN 15804+A2-compliant cement EPD [24]. For microsilica, the base-case factor of 0.599 kg CO_2-eq/kg was replaced by 0.643 kg CO_2-eq/kg, obtained from an alternative verified EPD for microsilica[25]. The latter EPD identifies microsilica as a by-product of silicon or ferrosilicon production and is prepared according to EN 15804+A2[25].

The material-related GWP of the modified composition was recalculated according to Equation (1) using these conservative factors. The resulting GWP increased from 311.09 to 315.46 kg CO_2-eq/m³. Nevertheless, according to Equation (2), the modified composition still provided an approximately 11.2% reduction relative to the reference value of 355.16 kg CO_2-eq/m³.

The corresponding performance-normalized carbon intensity, calculated according to Equation (5), increased only slightly from 74.07 to 75.11 kg CO_2-eq/(m³·MPa) under the conservative scenario. This value remained approximately 36.6% lower than that of the reference mixture.

The sensitivity analysis therefore indicates that the environmental advantage of the modified composition was not dependent on a single low-burden assumption for fly ash and microsilica. Even when higher GWP factors were assigned to the secondary mineral components, the FA15–MS5 mixture maintained lower material-related GWP and substantially lower carbon intensity than the reference composition.

These results also demonstrate the importance of evaluating cement substitution together with material performance rather than considering the replacement percentage alone. In the present case, the modified composition combined reduced Portland-cement consumption with increased compressive strength, resulting in a greater mechanical performance per unit of material-related greenhouse-gas burden.

Environmental Implications and Limitations: The results of the present study indicate that the environmental benefit of the modified D800 foam concrete arises primarily from the combined reduction in Portland-cement consumption and the incorporation of secondary industrial mineral materials. Replacing 20% of the cement with fly ash and microsilica reduced the material-related GWP by 12.4% under the base-case assumptions, while the performance-normalized carbon intensity decreased by 37.4%. The sensitivity analysis further showed that this advantage was maintained when more conservative environmental burdens were assigned to the two secondary mineral components.

From a resource-efficiency perspective, the FA15–MS5 composition incorporated 83 kg/m³ of secondary industrial mineral materials, thereby reducing the demand for an equivalent mass of clinker-containing cement. This approach is consistent with circular-economy strategies in which industrial by-products are redirected from disposal or low-value applications toward productive use in construction materials. However, the environmental benefit should not be interpreted as resulting from waste utilization alone; as demonstrated in in the Material-Related GWP and Resource Efficiency and Carbon–Strength Efficiency and Sensitivity Analysis sections, the environmental burdens associated with the processing and supply of fly ash, microsilica and chemical admixtures must also be considered.

The cellular structure of foam concrete provides an additional potential environmental advantage during the use stage. Foamed concrete is characterized by comparatively low thermal conductivity because of its highly porous structure, and its use in building envelopes can contribute to reduced heat transfer and improved thermal insulation[3,5]. Nevertheless, operational energy savings were not quantified in the present study, because whole-building energy simulation and in-service monitoring were outside the scope of the research. Therefore, the potential reduction in heating or cooling demand should be regarded as an additional prospective benefit rather than as part of the calculated GWP reduction.

The non-autoclaved production route may also offer an energy-related advantage because it eliminates the high-temperature, high-pressure autoclaving stage required for autoclaved cellular concretes. However, the actual electricity and thermal-energy consumption of foam generation, mixing, casting and curing were not measured in the present study. Consequently, no numerical production-energy or production-stage carbon benefit was assigned to the non-autoclaved process, and these contributions were excluded from the material-related GWP assessment.

Several limitations of the environmental assessment should therefore be acknowledged. First, the study represents a partial product carbon-footprint assessment rather than a complete life-cycle assessment. Transportation of raw materials, manufacturing energy, construction activities, service-life effects and end-of-life processes were not included. Second, product-specific environmental data were not available for all experimentally used materials, and verified proxy EPDs were therefore applied as described in the Environmental Assessment section. Third, environmental burdens attributed to secondary industrial materials are sensitive to allocation and processing assumptions; this uncertainty was addressed through the sensitivity analysis, but it cannot be eliminated completely.

A further environmental consideration concerns the chemical composition of coal fly ash. Fly ash may contain trace metals and metalloids whose mobility depends on ash composition, pH and exposure conditions, and leaching behavior has therefore been identified as an important consideration in its beneficial reuse[26]. No dedicated leaching or ecotoxicity tests were performed within the present study. Consequently, the present results demonstrate reductions in material-related GWP and improved resource utilization, but they should not be interpreted as a complete assessment of the environmental safety of the fly-ash-containing material. Future work should therefore combine carbon-footprint evaluation with leaching assessment and broader life-cycle impact categories.

Overall, the results show that the environmental value of the FA15–MS5 composition is not based solely on replacing Portland cement with secondary materials. Its main advantage lies in combining reduced cement demand, utilization of industrial by-products, lower material-related GWP and improved mechanical performance within the same D800 non-autoclaved foam-concrete system. These findings support the further development of performance-based low-carbon cellular materials, while also highlighting the need for broader life-cycle and environmental-safety assessments before their full environmental performance can be established.

Conclusion

The study demonstrated that the optimized D800 non-autoclaved foam-concrete composition incorporating fly ash and microsilica as partial cement replacements achieved improved material-related carbon and functional performance compared with the reference composition.The FA15–MS5 composition reduced Portland-cement consumption by 20% while incorporating 83 kg/m³ of secondary industrial mineral materials and simultaneously increasing the 28-day compressive strength.

The material-related GWP was reduced by approximately 12.4%, while the performance-normalized carbon intensity improved by about 37.4%. The sensitivity analysis confirmed that this environmental advantage remained evident even when more conservative GWP factors were applied to fly ash and microsilica.

The modified composition also exhibited an approximately 18.1% reduction in thermal conductivity, indicating improved thermal-insulation performance. This may provide an additional environmental benefit during building operation through reduced heat transfer and potentially lower heating and cooling energy demand, although these use-stage effects were not quantified in the present study.

Overall, the FA15–MS5 composition combines reduced cement demand, utilization of secondary industrial materials, lower material-related carbon burden, improved mechanical performance and enhanced thermal-insulation properties. The present assessment represents a partial product carbon-footprint study; future research should include production energy, transportation, operational energy performance, broader life-cycle impact categories and leaching assessment.

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