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Composition Design and Performance Evaluation of Non-Autoclaved Cement–Fly Ash Foam Concrete Modified with Wollastonite And Basalt Fiber

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Abstract

The paper presents a scientifically grounded composition-design approach for non-autoclaved cement–fly ash foam concrete modified with wollastonite and basalt fiber. The study is focused on the stabilization of the cellular structure, strengthening of interpore partitions and improvement of the balance between thermal insulation and mechanical performance. A two-stage preparation route was adopted: technical foam was produced separately and then introduced into a cement–fly ash matrix containing dispersed wollastonite and, when required, basalt fiber. The main controlled parameters were water-to-solid ratio, cement-to-fly ash ratio, foam density, wollastonite fraction and dosage, wollastonite fineness, and fiber content. The results indicate that dispersed wollastonite at 1.0–1.5% of binder mass reduces fresh-mixture settlement from 14 mm in the control mixture to about 6 mm and increases the foam stability index to 0.94–0.95 at a specific surface of approximately 300 m²/kg. The most effective method of addition was dry blending with cement and fly ash, which produced a dry density of 532 kg/m³, thermal conductivity of 0.128 W/(m·°C), and 28-day compressive strength of 1.92 MPa. Compared with the control mixture, the combined dispersed-wollastonite and basalt-fiber modification increased 28-day compressive strength by about 48%, reduced drying shrinkage by about 27%, and increased the closed-pore fraction from 46% to 52%.

Keywords: Foam concrete; cement–fly ash binder; Koytash wollastonite; basalt fiber; thermal conductivity; compressive strength; cellular structure; shrinkage.

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1. Introduction

Energy-efficient building envelopes require materials that combine low density, low thermal conductivity, fire safety, durability and economic feasibility. Non-autoclaved foam concrete is one of the most promising lightweight cementitious materials for this purpose because its cellular structure enables a significant reduction in the solid skeleton fraction. In hot and dry climates, however, the stability of such cellular systems becomes difficult to maintain: rapid moisture loss accelerates early-age shrinkage, promotes microcracking and may reduce the long-term stability of thermal-insulation characteristics.

The main technological challenge of foam concrete is not only to create pores, but also to preserve them until the cementitious matrix obtains sufficient structural strength. If the foam is chemically or physically incompatible with the cement–mineral paste, drainage, coalescence, settlement and segregation occur. These processes increase dry density and thermal conductivity while reducing compressive strength. Therefore, a rational foam-concrete design must simultaneously control foam stability, rheology of the cementitious paste, hydration kinetics, and the geometry and strength of interpore partitions.

The use of fly ash as a mineral component in foam concrete is technologically and economically justified. Fine spherical particles can improve workability, reduce water separation and contribute to pozzolanic densification of the cement matrix at later ages. Nevertheless, fly ash alone may not provide sufficient early structural strength in non-autoclaved systems. This limitation is especially critical in mixtures with high air volume, where weak interpore partitions can become the decisive failure zones under mechanical load.

A practical way to overcome this limitation is the incorporation of mineral modifiers that are chemically compatible with cement hydration products and capable of acting as nucleation centers and microfilling particles. Wollastonite, a calcium silicate mineral with a chain-like structure, is particularly suitable for this function because its Ca–Si composition is close to that of cement hydrates, while its elongated particles can contribute to micro-reinforcement. In this study, Koytash (Jizzakh) wollastonite is considered in two forms: ore fraction and dispersed fraction. The dispersed fraction is expected to create a larger number of nucleation sites, densify the interpore partitions and reduce open capillary porosity.

Basalt fiber was used as an additional micro-reinforcing component. Its role is to limit early-age shrinkage cracking, redistribute local tensile stresses and increase the crack-growth resistance of the cellular matrix. The combination of dispersed wollastonite and basalt fiber is therefore based on a synergistic concept: wollastonite stabilizes the pore walls and accelerates structural formation, while fiber bridges microcracks and improves deformation stability. The aim of this paper is to evaluate this concept using experimental data on fresh mixture stability, dry density, compressive strength, thermal conductivity, pore structure and drying shrinkage.

2. Methods

2.1. Raw materials

The material system was designed using locally available raw materials. Portland cement CEM I 32.5 and CEM I 42.5 were used as binders. Fly ash from the Yangi Angren thermal power plant served as a fine aluminosilicate component and partial binder replacement. Koytash wollastonite from the Jizzakh region was used in ore and dispersed forms. The dispersed fraction was produced by drying, grinding and classification of the ore material. Protein-based “Etalon” and synthetic “PB-2000” foaming agents were considered for foam production, while the optimized compositions used a protein-based foaming solution due to its higher foam stability. Basalt fiber was incorporated to reduce shrinkage-related microcracking.

Table 1. Raw materials used for the investigated foam-concrete system.

Material	Source or type	Function in the composite
Portland cement	CEM I 32.5 / CEM I 42.5	Hydraulic binder and early structural strength
Fly ash	Yangi Angren TPP	Fine filler, pozzolanic component, rheology modifier
Wollastonite ore	Koytash, Jizzakh	Raw source for dispersed mineral modifier

Dispersed wollastonite	Ground and classified fraction	Nucleation center, microfiller, pore-wall modifier
Protein foaming agent	Etalon, 2.5% working solution	Stable technical foam and pore formation
Synthetic foaming agent	PB-2000	Comparative foam-generation system
Basalt fiber	6-12 mm length, mineral fiber	Micro-reinforcement and shrinkage-crack control
Water	Drinking-quality water	Mixing and foam-generation medium

2.2. Preparation of wollastonite fractions

The wollastonite ore was dried to reduce moisture-related agglomeration, then crushed and ground in a laboratory mill. Classification was performed to obtain a dispersed fraction with a target specific surface of approximately 2000–4000 cm²/g, corresponding in the present experimental interpretation to a functional fineness of about 200–450 m²/kg. The optimum working region was found near 300 m²/kg because lower fineness did not provide sufficient microfilling, whereas excessive fineness increased water demand and could intensify drainage in the foam films. No electrolyte additives were used; stability was controlled through foaming-agent concentration, water-to-solid ratio, wollastonite dosage and fineness.

Table 2. Comparative characteristics of Koytash wollastonite fractions.

Parameter	Ore fraction	Dispersed fraction
Mineralogical basis	Wollastonite-bearing ore	Predominantly wollastonite after grinding/classification
Indicative oxide composition	SiO2 45-52%; CaO 43-50%	SiO2 48-52%; CaO 46-50%
Density	≈2600-2900 kg/m³	≈2600-2900 kg/m³
Specific surface	≈400-800 cm²/g	≈2000-4000 cm²/g
Median particle size	≥100 μm	≈8-20 μm
Main technological role	Coarse stabilizing filler	Pore-wall modifier and nucleation agent

2.3. Foam-concrete preparation

A two-stage preparation route was used. First, a technical foam was produced from a working foaming-agent solution. Second, a cement–fly ash paste containing wollastonite and, when required, basalt fiber was prepared separately. Dry components were mixed for 1.5–2 min to ensure uniform distribution of fly ash and wollastonite. Water was then added and the paste was homogenized for 3–4 min. Finally, technical foam was introduced and the mixture was blended for 1–2 min under a low-intensity regime in order to avoid bubble destruction. The prepared mixtures were cast without vibration, protected against rapid moisture loss and cured at 20±2 °C. Mechanical and physical tests were performed at 7, 28 and 90 days where applicable.

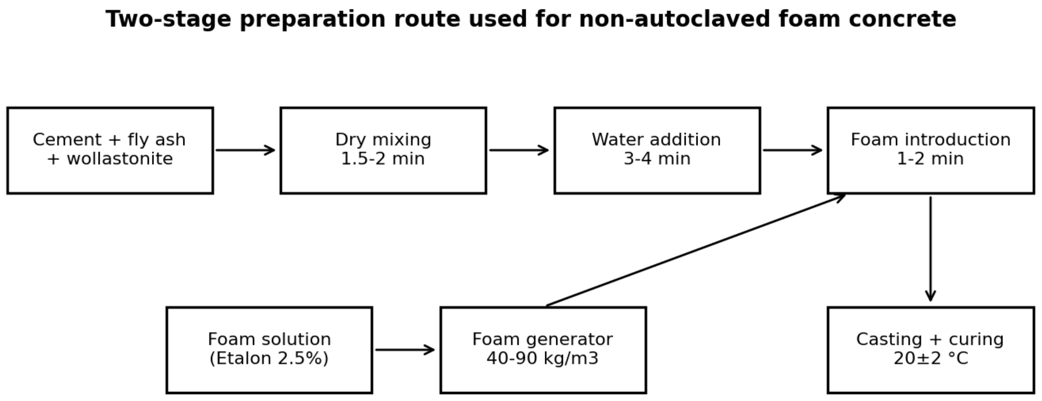

Figure 1. Preparation route and main technological control points for the investigated foam concrete.

2.4. Mix design and test methods

The control mixture was selected after optimizing the cement–fly ash ratio and water-to-solid ratio. The most stable base composition corresponded to a fly ash-to-cement ratio of 0.60 and W/S = 0.49. In this state, the foam multiplicity was 18.3, the foam stability index was 0.74, dry density was approximately 560 kg/m³, 28-day compressive strength was about 1.28 MPa, and thermal conductivity was 0.125 W/(m·°C). Modified compositions were then developed by varying wollastonite fraction, wollastonite dosage and basalt fiber content.

Fresh-mixture stability was evaluated by settlement after 60 min and by qualitative observation of segregation. Foam stability was assessed using the stability index Spct. Hardened properties included dry density, compressive strength at 7, 28 and 90 days, thermal conductivity, pore-system indicators and drying shrinkage. The results were interpreted using a structure-property approach in which foam stability, pore distribution, open capillary porosity and interpore partition strength are considered as mutually linked parameters.

Table 3. Foam-concrete compositions developed on the basis of optimized parameters.

Mix	Target class	Cement, kg/m³	Fly ash, kg/m³	Water, L/m³	Foam solution, L/m³	Wollastonite	Fiber, kg/m³
T0	D600	235	141	184	410	-	0.0
T1	D600	230	138	182	420	Ore 1.0%	1.0
T2	D600	230	138	183	425	Dispersed 1.5%	1.0
T3	D600	228	137	183	430	Dispersed 1.5%	1.5
T4	D500	210	126	168	480	Dispersed 1.5%	1.5
T5	D400	185	111	152	540	Dispersed 1.5%	1.5

3. Results

3.1. Fresh-mixture stability

The stability of the fresh foam-concrete mixture improved considerably when Koytash wollastonite was introduced, especially in dispersed form. The control mixture showed a settlement of 14 mm after 60 min and visible signs of pore coalescence. The ore fraction reduced settlement to 9–11 mm, indicating a stabilizing effect, but its influence was limited by the larger particle size and a stronger filler-like role. In contrast, dispersed wollastonite reduced settlement to 6–8 mm, and at 1.0–1.5% dosage segregation was not visually observed.

Table 4. Influence of wollastonite fraction and dosage on fresh-mixture settlement.

Wollastonite form	Dosage, %	Settlement after 60 min, mm	Segregation signs
Control	0	14	Moderate
Ore fraction	0.5	11	Low
Ore fraction	1.0	9	Low
Ore fraction	1.5	10	Low; rheology becomes heavier
Dispersed fraction	0.5	8	Almost none
Dispersed fraction	1.0	6	None
Dispersed fraction	1.5	6	None
Dispersed fraction	2.0	7	Low; water demand increases

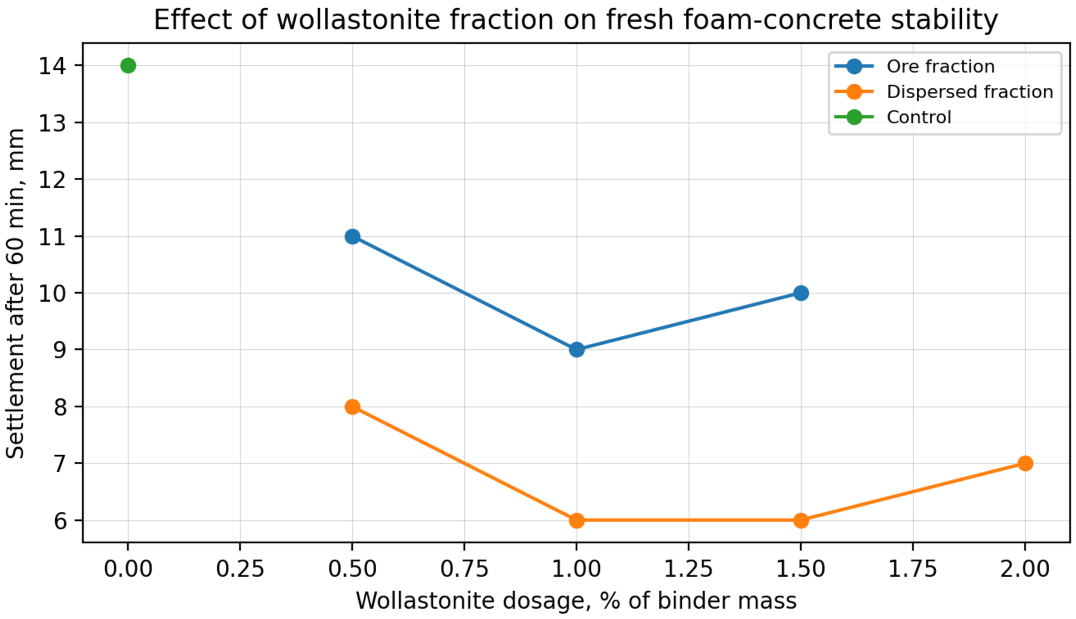

Figure 2. Settlement of fresh foam concrete depending on wollastonite fraction and dosage.

The improvement in fresh stability can be explained by the combined effects of microfilling, mechanical protection of foam films and partial blocking of liquid drainage channels. Dispersed wollastonite particles are small enough to enter the interpore partitions and form a mineralized layer around bubbles. This layer reduces the probability of bubble coalescence and provides a more uniform pore-size distribution. The slight deterioration at 2.0% dosage is attributed to increased water demand and agglomeration risk, which can locally disturb the foam films.

3.2. Effect of wollastonite fineness on foam stability

The foam stability index Spct was sensitive not only to dosage, but also to wollastonite fineness. The highest values were obtained at a specific surface close to 300 m²/kg and a dosage of 1.0–1.5%. At this fineness, Spct reached 0.94–0.95, whereas both lower and higher fineness produced slightly lower stability. The result confirms that the modifier should not be judged only by mineralogical composition; its particle-size distribution controls whether it acts as an effective pore-wall stabilizer or as a water-demand-increasing powder.

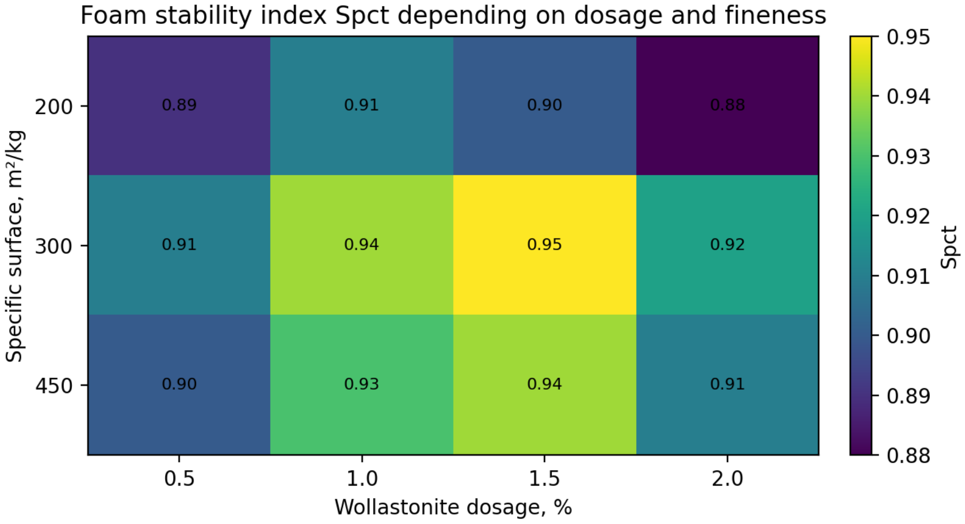

Figure 3. Foam stability index as a function of dispersed-wollastonite dosage and fineness.

3.3. Influence of the method of wollastonite addition

Three technological methods of wollastonite addition were compared: pre-dispersion in water, mineralization in the foaming solution, and dry blending with cement and fly ash. Dry blending produced the best combination of dry density, thermal conductivity and compressive strength. This method gave a dry density of 532 kg/m³, thermal conductivity of 0.128 W/(m·°C), and 28-day compressive strength of 1.92 MPa. The advantage is associated with more uniform particle distribution in the cement–fly ash matrix and better formation of a mineral skeleton in the interpore partitions.

Table 5. Influence of wollastonite addition method on key foam-concrete properties.

Addition method	Description	Dry density, kg/m³	λ, W/(m·°C)	R28, MPa
I	Wollastonite pre-dispersed in water	545	0.132	1.70
II	Foam mineralization with wollastonite	540	0.131	1.82
III	Dry blending with cement and fly ash	532	0.128	1.92

3.4. Hardened properties

The combined modification with dispersed wollastonite and basalt fiber produced the most favorable balance between strength, density and thermal insulation. In comparison with the control mixture T0, mixture T3 had lower dry density (532 kg/m³ versus 560 kg/m³), lower thermal conductivity (0.128 versus 0.135 W/(m·°C)) and substantially higher compressive strength. At 28 days, compressive strength increased from 1.30 to 1.92 MPa, corresponding to a relative improvement of approximately 48%. At 90 days, the strength improvement remained significant, increasing from 1.55 to 2.25 MPa.

Table 6. Physical-mechanical and thermal characteristics of selected foam-concrete mixtures.

Mix	Density, kg/m³	λ, W/(m·°C)	R7, MPa	R28, MPa	R90, MPa	Shrinkage 28 d, mm/m
T0	560	0.135	0.85	1.30	1.55	1.12
T2	538	0.130	1.05	1.78	2.05	0.98
T3	532	0.128	1.15	1.92	2.25	0.82
T5	420	0.104	0.62	0.95	1.12	0.78

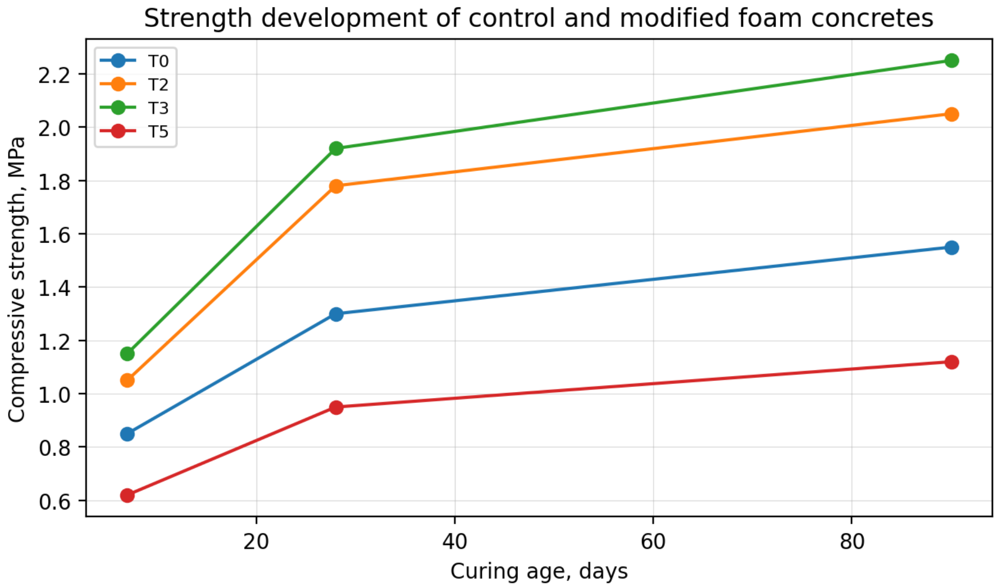

Figure 4. Compressive strength development of control and modified compositions.

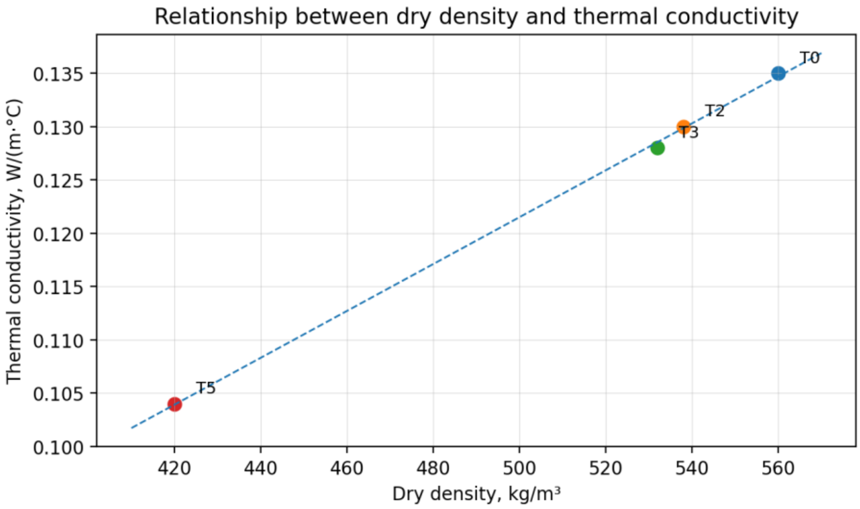

Figure 5. Relationship between dry density and thermal conductivity for selected compositions.

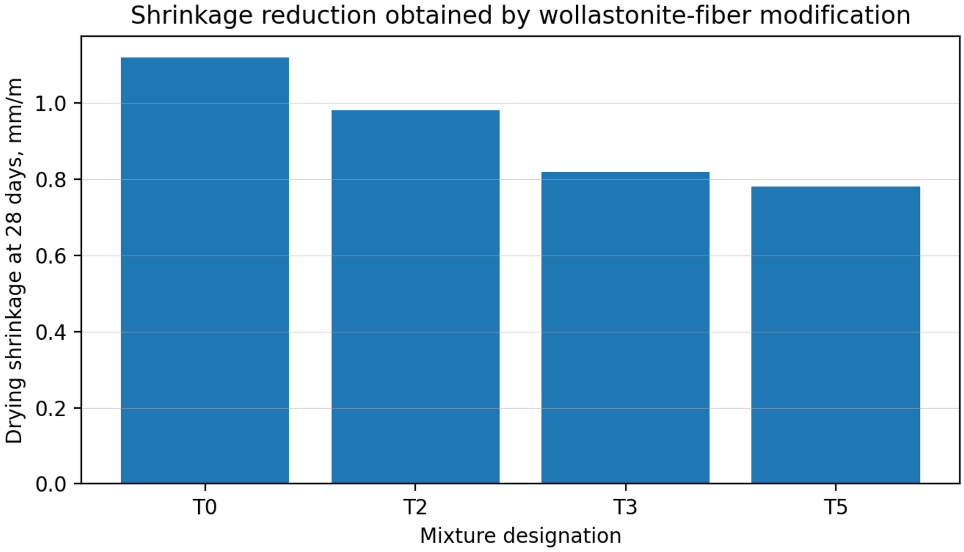

Figure 6. Drying shrinkage of control and modified mixtures at 28 days.

The D400 composition T5 reached the lowest thermal conductivity, 0.104 W/(m·°C), because of its reduced dry density and higher foam content. Although its compressive strength was lower than that of D600 mixtures, the 28-day value of 0.95 MPa remains relevant for thermal-insulation applications where the material is not the primary load-bearing component. This result demonstrates that the developed modification approach can be used not only for strengthening D600 foam concrete, but also for producing lower-density thermal-insulation grades.

3.5. Pore-system changes

The pore-system comparison between the control mixture and the combined modified mixture T3 confirms the structural mechanism behind the improvement in properties. Total porosity remained almost unchanged (62–63%), but the closed-pore fraction increased from 46% to 52% and open capillary porosity decreased from 16% to 11%. The average pore radius decreased from 0.65 to 0.40 mm, while the distribution coefficient decreased from 0.65 to 0.50, indicating a narrower and more uniform pore-size distribution. These changes are consistent with the observed reduction in thermal conductivity and shrinkage.

Table 7. Pore-system parameters of control and wollastonite-fiber modified foam concrete.

Pore-system parameter	Control T0	Modified T3
Total porosity, %	62	63
Closed-pore fraction, %	46	52
Open capillary fraction, %	16	11
Average pore radius, mm	0.65	0.40
Distribution coefficient	0.65	0.50

4. Discussion

The results show that the effect of Koytash wollastonite is governed by its fraction, dosage, fineness and addition method. The ore fraction provides a measurable stabilizing effect, but its larger particles mainly act as filler and cannot fully participate in microstructural densification of interpore partitions. The dispersed fraction is more effective because it can enter the thin cementitious films between adjacent pores, reduce local water migration, and provide nucleation surfaces for hydration products. This explains why the dispersed fraction at 1.0–1.5% dosage produced the lowest settlement and the highest foam stability index.

The microstructural interpretation is based on the chemical affinity between wollastonite and calcium silicate hydrate phases. In a cementitious medium, dispersed wollastonite particles can act as substrates for the precipitation of hydration products. At the same time, fly ash contributes to later-age pozzolanic densification by consuming calcium hydroxide and forming additional C–S–H. When these two mechanisms operate together, the interpore partitions become denser and less capillary, which reduces water absorption potential and decreases the probability of shrinkage-related microcracking.

Basalt fiber complements this mechanism through physical micro-reinforcement. In cellular concrete, failure frequently starts at thin pore walls and at microdefects around large pores. Fibers bridge these zones and force cracks to follow a more tortuous path, increasing the energy required for crack growth. This is why the T3 mixture, containing dispersed wollastonite and 1.5 kg/m³ of basalt fiber, demonstrated the highest strength among the tested thermal-insulation compositions. The 27% reduction in drying shrinkage relative to the control further confirms the deformation-stabilizing role of the fiber-modified mineral skeleton.

The relationship between density and thermal conductivity follows the expected trend: lower density generally reduces heat transfer through the solid skeleton. However, the comparison between T0 and T3 indicates that density alone does not fully explain thermal conductivity. T3 had only about 5% lower density than T0, but it also had a higher closed-pore fraction and a lower open capillary fraction. Closed, small and uniformly distributed pores limit convective transfer and moisture accumulation, which is especially important in hot-dry climates where cyclic drying and wetting may affect long-term thermal performance.

From a technological point of view, dry blending of wollastonite with cement and fly ash is preferable because it allows homogeneous distribution of the modifier before water addition and foam introduction. Pre-dispersion in water may cause agglomeration and local increases in viscosity, while addition through the foam solution demands stricter control of foam multiplicity and liquid film stability. Therefore, for small and medium production lines, dry addition provides the most robust and reproducible route.

The practical optimization window can be defined as follows: dispersed Koytash wollastonite with a specific surface around 300 m²/kg, dosage 1.0–1.5% of binder mass, basalt fiber 1.0–1.5 kg/m³, protein foaming agent at 2.5% working concentration, and a base cement–fly ash system close to fly ash/cement = 0.60 with $W/S \approx 0.49$. Within this region, the foam concrete maintains low thermal conductivity while reaching compressive strength levels sufficient for thermal-insulation and self-supporting applications.

5. Conclusions

The study confirms that Koytash wollastonite and basalt fiber can be effectively used to improve the structure and performance of non-autoclaved cement–fly ash foam concrete. The following conclusions are drawn from the obtained experimental data:

- Dispersed wollastonite is more effective than the ore fraction for stabilizing the fresh foam-concrete mixture. At 1.0–1.5% of binder mass it reduced settlement from 14 mm to about 6 mm and eliminated visible segregation.
- The optimum fineness of dispersed wollastonite was near 300 m²/kg. At this level, the foam stability index reached 0.94–0.95; finer material did not provide additional benefit because water demand and drainage risk increased.
- The most effective addition method was dry blending with cement and fly ash. This method produced 532 kg/m³ dry density, 0.128 W/(m·°C) thermal conductivity and 1.92 MPa 28-day compressive strength.
- Combined modification with dispersed wollastonite and basalt fiber increased 28-day compressive strength by approximately 48%, increased 90-day strength by about 45%, and reduced 28-day drying shrinkage by about 27% compared with the control mixture.
- The improvement is explained by a structural mechanism involving foam-film mineralization, nucleation of hydration products on wollastonite particles, microfilling of pore walls, basalt-fiber crack bridging, increased closed-pore fraction and reduced open capillary porosity.
- The developed compositions are suitable for thermal-insulation foam-concrete applications in hot and dry climates, provided that early moisture loss during the first 24–48 hours is limited by appropriate curing and surface protection.

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