

# Optimization and Performance Evaluation of Non-Autoclaved D400 Foam Concrete Modified With GGBFS-Type Slag, Activated Natural Zeolite and Sika® Viscocrete®-1095

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## Abstract

*The present study develops and evaluates a non-autoclaved D400 foam concrete modified by a multi-component chemical-mineral system based on a locally applicable GGBFS-type slag, activated natural zeolite, a metakaolin-gypsum complex modifier, an AS setting accelerator and the polycarboxylate ether superplasticizer Sika® ViscoCrete®-1095. The work was aimed at improving the performance of low-density foam concrete without increasing its density beyond the D400 class. Cement paste tests were first used to determine the safe accelerator range by normal consistency and setting time. Fine-grained cement-sand systems were then used to separate the effect of accelerator dosage and water-reducing admixture from the instability of foam. Finally, eight D400 foam concrete compositions were prepared and tested under normal curing and thermal-moisture curing. Strength, density, thermal conductivity, water absorption, softening coefficient, moisture loss, shrinkage deformation, XRD/DTA/TG and SEM indicators were analyzed. The rational composition contained 30% GGBFS-type slag, 8% complex modifier, 0.07% AS accelerator and Sika® ViscoCrete®-1095. Compared with the control D400 composition, the optimized system increased 28-day compressive strength from 2.21 to 4.57 MPa under normal curing and from 1.58 to 3.35 MPa after thermal-moisture curing. Thermal conductivity decreased to 0.073-0.080 W/(m·°C), water absorption decreased from 53.2% to 17.3%, and shrinkage decreased to 0.64-0.68 mm/m. The results confirm that a combined dispersion-packing and early-structure-stabilization approach is effective for producing high-performance non-autoclaved foam concrete from locally adaptable mineral resources.*

**Keywords:** Non-autoclaved foam concrete; D400; GGBFS-type slag; activated natural zeolite; PCE superplasticizer; AS accelerator; shrinkage; thermal conductivity; microstructure.

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## 1. Introduction

Low-density foam concrete is a promising wall and thermal-insulation material because it combines reduced self-weight, low thermal conductivity and relatively simple production technology. However, the practical use of non-autoclaved foam concrete in the D400 density class is often limited by the instability of the foam-cement matrix, capillary porosity, drying shrinkage and insufficient early strength. These limitations are especially important for enclosing structures, where the material must retain not only low density but also sufficient mechanical integrity and stable heat-transfer characteristics during long-term service.

The performance of foam concrete is controlled by a coupled system of factors: the activity and particle-size distribution of the binder, the stability of the foam, the rheology of the cement paste, the hydration kinetics, the structure of inter-pore partitions and the moisture regime of the hardened material. Increasing the amount of solid phase in the inter-pore partitions without excessive water demand is therefore a key technological objective. Mineral additions with different dispersion levels can fill interparticle voids, provide pozzolanic or latent hydraulic reactions and reduce capillary channels. At the same time, a modern water-reducing admixture is required to preserve workability at a low water-to-solid ratio.

In this work, the matrix was modified using a GGBFS-type slag as a latent hydraulic component, activated natural zeolite as a fine aluminosilicate microfiller and pozzolanic component, a metakaolin-gypsum modifier to support ettringite-related volume compensation, and

Sika® ViscoCrete®-1095 as a PCE-based superplasticizer. The AS accelerator was used to increase early structuring of the cement system and to reduce the risk of foam collapse during the initial hardening stage. The central hypothesis was that a multi-level dispersion structure combined with controlled setting kinetics can simultaneously improve strength, reduce shrinkage and maintain low thermal conductivity in D400 non-autoclaved foam concrete.

The objective of the study was to establish a rational composition and to evaluate its influence on the main performance indicators of D400 foam concrete. The novelty of the article lies in the integrated assessment of accelerator dosage, PCE-assisted water reduction, GGBFS-zeolite-based mineral modification and structural performance indicators within one technology-oriented framework.

## 2. Methods

The binder system consisted of CEM I 42.5N Portland cement, GGBFS-type finely ground metallurgical slag, activated natural zeolite, a metakaolin-gypsum complex modifier (MB-B-II-2 type), AS setting accelerator and Sika® ViscoCrete®-1095 superplasticizer. A PB-2000-type foam agent was used to generate technical foam. Quartz sand was used in cement-sand preliminary tests. Water meeting the requirements for concrete mixing water was used throughout. The materials were selected to provide a stable industrial raw-material basis and to ensure compatibility with the subsequent D400 foam concrete technology.

**Table 1. Materials used and their functional role in the modified foam concrete system.**

Material/component	Function in the system	Technological role
CEM I 42.5N Portland cement	Primary binder	Provides hydration products and the main strength-forming matrix.
GGBFS-type finely ground slag	Latent hydraulic mineral addition	Improves particle packing, contributes to additional C-S-H-type phases and reduces pore connectivity.

Activated natural zeolite	Fine aluminosilicate microfiller and pozzolanic component	Adsorbs water in the microstructure, reacts with Ca(OH) <sub>2</sub> and stabilizes inter-pore partitions.
Metakaolin-gypsum complex modifier (MB-B-II-2 type)	Chemical-mineral modifier	Supports aluminosilicate reaction and ettringite-related shrinkage compensation.
Sika® ViscoCrete®-1095	PCE superplasticizer	Reduces water demand and improves dispersion of the fine mineral phase.
AS accelerator	Setting and hardening accelerator	Accelerates early structure formation and limits foam-matrix instability.
PB-2000-type foam agent	Foaming component	Forms the controlled air-pore structure required for D400 density.

**Table 2. Recommended material consumption for the optimized D400 foam concrete composition.**

Component	Consumption for 1 m <sup>3</sup>	Comment
Portland cement (CEM I 42.5N)	160 kg	Primary binder, 40% of solid binder system.
GGBFS-type finely ground slag	120 kg	30% mineral component, latent hydraulic microfiller.
Complex modifier (activated zeolite + MB-B-II-2, 1:1)	20 kg	8% of solid system; includes zeolite, metakaolin/gypsum effect.
AS accelerator	2.8 kg	Working solution dosage; dry matter corresponds to approx. 0.07% in the selected design.
Water	97 kg	Water-to-solid ratio about 0.32; foam solution water accounted separately in production practice.

**Experimental design and testing procedure**

The experimental program was conducted in three consecutive stages. In the first stage, cement paste tests were used to evaluate the influence of AS accelerator on normal consistency and setting times. The dosage of AS

was varied from 0 to 3% of cement mass. The purpose of this stage was to identify a dosage interval that accelerates setting without causing excessive water demand or flash setting.

In the second stage, fine-grained cement-sand concrete was tested to evaluate the combined effect of AS accelerator and Sika® ViscoCrete®-1095 at a constant workability level. This stage made it possible to study the accelerator under conditions where the density variation caused by foam is excluded. The cement:sand ratio was 1:4, and the spread of the mixture was maintained at 27-28 cm.

In the third stage, D400 foam concrete compositions were prepared in a laboratory mixer. The foam was generated separately and then introduced into the mineral binder system. The target density class was D400. The specimens were cured under two regimes: normal curing (NC) and thermal-moisture curing (TMC). The main measured properties included average density,

$$R_c = 4.500 + 0.117X_1 - 0.100X_1X_2 - 0.850X_1^2 - 0.300X_2^2 \quad (R^2 = 0.962)$$

$$\lambda = 0.07353 - 0.00050X_1 + 0.00067X_2 + 0.00100X_1X_2 + 0.00618X_1^2 + 0.00268X_2^2 \quad (R^2 = 0.927)$$

where X1 and X2 are coded variables for the GGBFS-type slag and complex modifier, respectively.

compressive strength, thermal conductivity, water absorption, softening coefficient, moisture loss and shrinkage deformation. The structure and phase composition were evaluated using DTA/TG, X-ray diffraction and scanning electron microscopy.

**Response-surface model**

A two-factor experimental design was used to evaluate the simultaneous influence of GGBFS-type slag (X1) and complex modifier content (X2). The coded levels corresponded to 20-40% for GGBFS-type slag and 4-12% for the complex modifier. The target responses were compressive strength R<sub>c</sub> and thermal conductivity λ. The fitted second-order models obtained from the experimental design were:

**3. Results**

**Effect of AS accelerator on cement paste**

The AS accelerator did not change the normal consistency of cement paste in the dosage interval 0.05-0.08%, where the value remained 24.75%. Increasing the

dosage above this range gradually increased water demand, while setting time shortened sharply. At 0.3% AS, the initial setting time decreased to 1 h 50 min and the final setting time to 5 h 10 min. At 3% AS, setting became extremely rapid. Therefore, 0.05-0.10% was accepted as a rational range for subsequent compositions, with 0.07% used in the optimized foam concrete.

**Table 3. Selected cement paste results used to determine the rational AS dosage interval.**

AS dosage, %	Normal consistency, %	Initial setting, h:min	Final setting, h:min
0	24.75	4:00	8:30
0.05	24.75	3:50	8:10
0.07	24.75	3:40	8:00
0.1	25.25	3:20	6:30
0.3	25.75	1:50	5:10
0.5	26.00	1:10	4:30
1	27.00	0:50	2:10
3	28.25	0:15	0:25

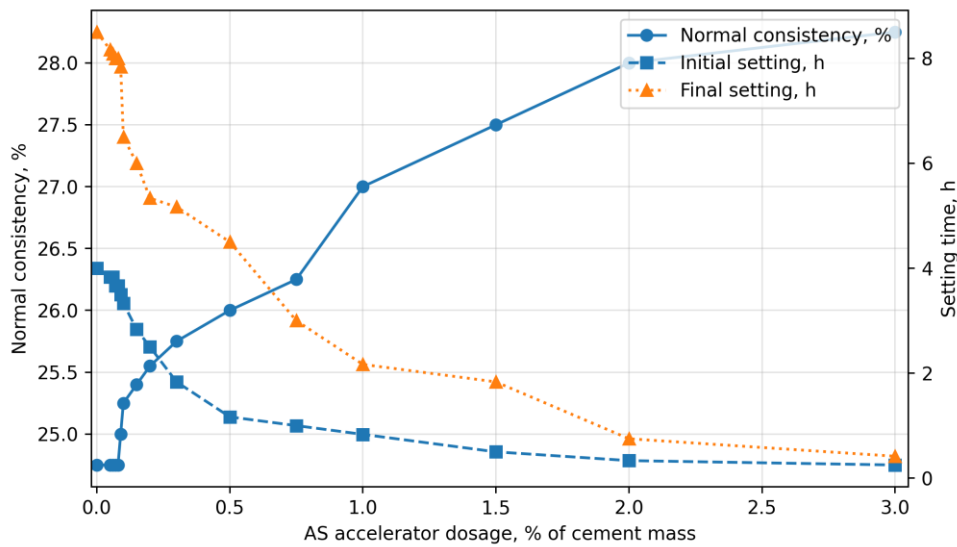


Figure 1. Influence of AS accelerator dosage on normal consistency and setting time of cement paste.

Optimization of the D400 foam concrete composition  
 Eight foam concrete compositions were compared at approximately the same target density. The introduction of 40% GGBFS-type slag alone improved 28-day strength and reduced thermal conductivity; however, the best combination of mechanical and hygrothermal performance was obtained for composition 8. This composition combined 30% GGBFS-type slag, 8%

complex modifier and 0.07% AS accelerator. Under normal curing, the 28-day compressive strength increased from 2.21 MPa for the control to 4.57 MPa for the optimized composition. After thermal-moisture curing, strength increased from 1.58 to 3.35 MPa. The optimized composition also showed the lowest thermal conductivity and shrinkage among the compared systems.

Table 4. Key construction-technical properties of selected D400 foam concrete compositions.

Composition	Density, kg/m <sup>3</sup>	R <sub>c</sub> , MPa (NC)	R <sub>c</sub> , MPa (TMC)	λ, W/(m·°C) (NC)	λ, W/(m·°C) (TMC)	Shrinkage, mm/m (NC)	Shrinkage, mm/m (TMC)
Control	398	2.21	1.58	0.109	0.110	2.54	2.99
40% GGBFS	384	3.84	2.05	0.072	0.085	1.01	2.60
Optimized: 30% GGBFS + 8% CM + 0.07% AS	381	4.57	3.35	0.073	0.080	0.64	0.68

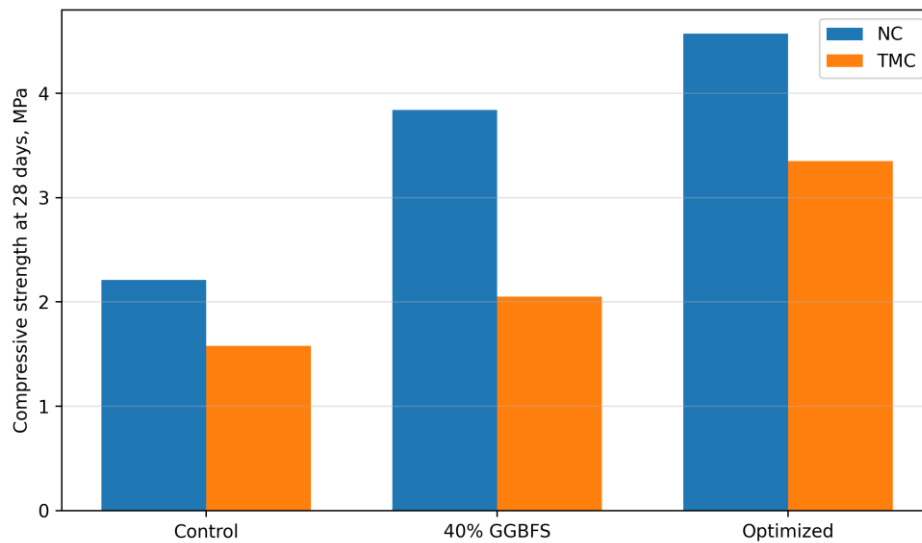


Figure 2. Comparison of 28-day compressive strength under normal curing and thermal-moisture curing.

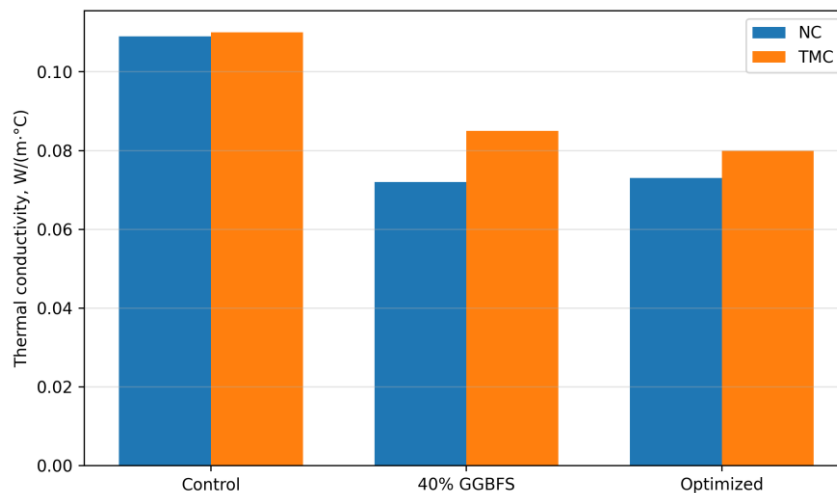


Figure 3. Thermal conductivity of selected D400 foam concrete compositions.

**Response-surface analysis**

The response-surface models indicate that the most favorable region is located near 30% GGBFS-type slag and 8% complex modifier. A further increase in slag or complex modifier content does not provide additional

improvement and can increase water demand or reduce the efficiency of the pore structure. The central point of the design produced compressive strength values of 4.55-4.58 MPa and thermal conductivity of 0.073 W/(m·°C), which confirms the stability of the optimized region.

Table 5. Two-factor design for strength and thermal conductivity responses.

Run	GGBFS, %	Complex modifier, %	R <sub>c</sub> , MPa	λ, W/(m·°C)
1	20	4	3.20	0.082
2	20	8	3.50	0.081
3	20	12	3.30	0.083
4	30	4	4.00	0.078

5	30	8	4.57	0.073
6	30	8	4.55	0.073
7	30	8	4.58	0.073
8	30	12	4.20	0.076
9	40	4	3.70	0.079
10	40	8	3.60	0.080
11	40	12	3.40	0.084

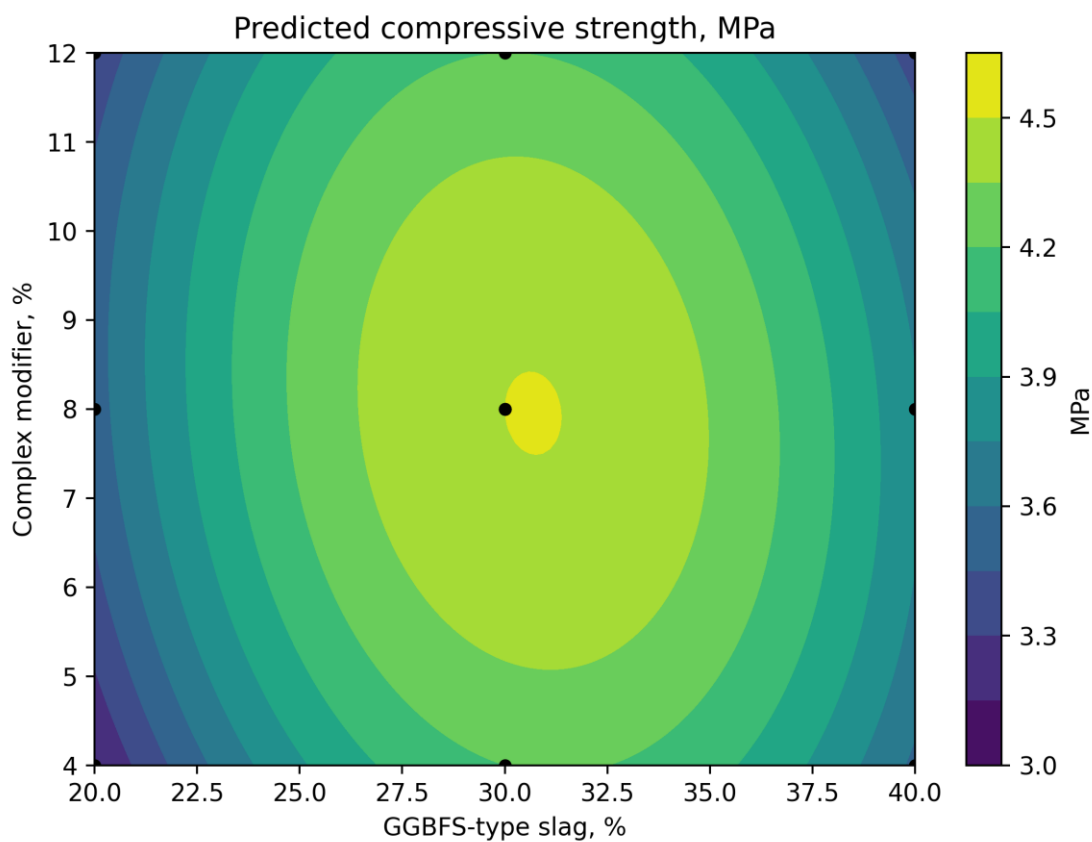


Figure 4. Response surface for predicted compressive strength as a function of GGBFS-type slag and complex modifier content.

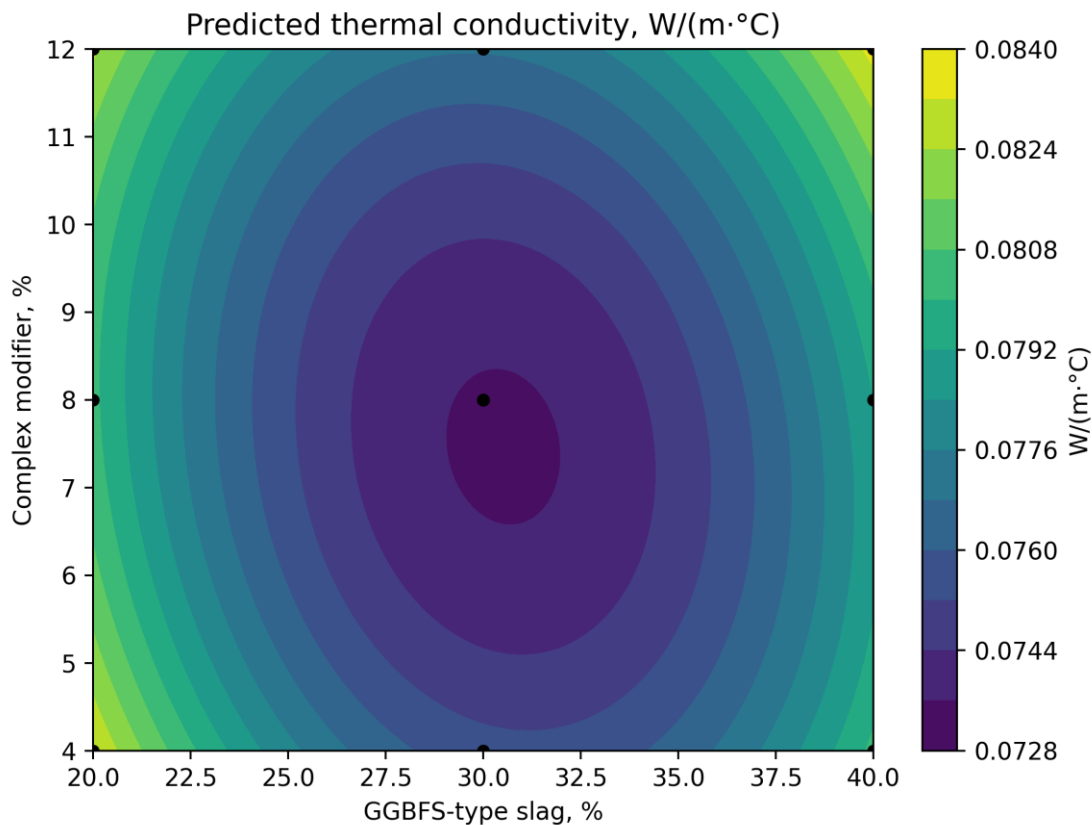


Figure 5. Response surface for predicted thermal conductivity as a function of GGBFS-type slag and complex modifier content.

**Water absorption, moisture regime and shrinkage**

The optimized composition showed a substantial reduction in water absorption and moisture retention. Water absorption decreased from 53.2% for the control to 17.3% for the optimized composition, while the softening coefficient increased from 0.65 to 0.88. Moisture content after 180 days decreased from 10.7% in

the control to 1.6% in the optimized composition. Shrinkage deformation stabilized much earlier and remained at 0.64-0.68 mm/m, compared with approximately 2.99 mm/m for the control. These results are consistent with a denser inter-pore matrix and a lower volume of connected capillary pores.

Table 6. Hygrophysical and shrinkage indicators of selected compositions.

Composition	Water absorption Wm, %	Softening coefficient	Moisture after 180 days, %	Final shrinkage (NC), mm/m	Final shrinkage (TMC), mm/m
Control	53.2	0.65	10.7	2.99	2.99
40% GGBFS	25.6	0.75	3.2	1.30	2.60
Optimized	17.3	0.88	1.6	0.64	0.68

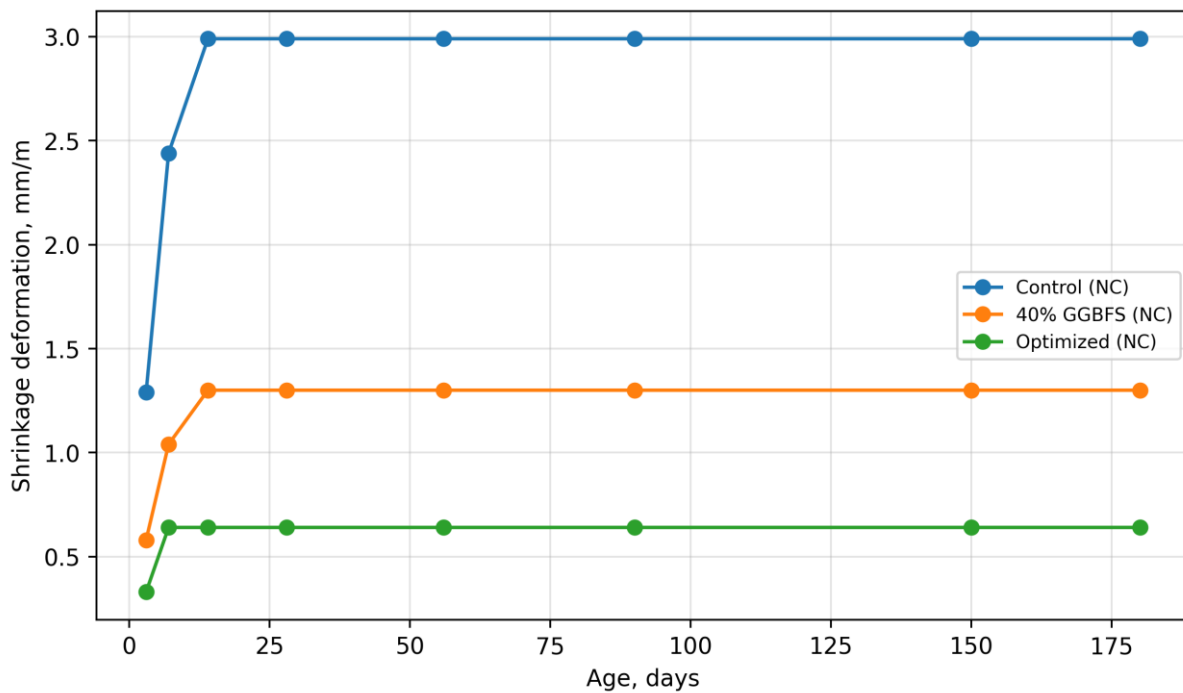


Figure 6. Shrinkage development of selected compositions under normal curing.

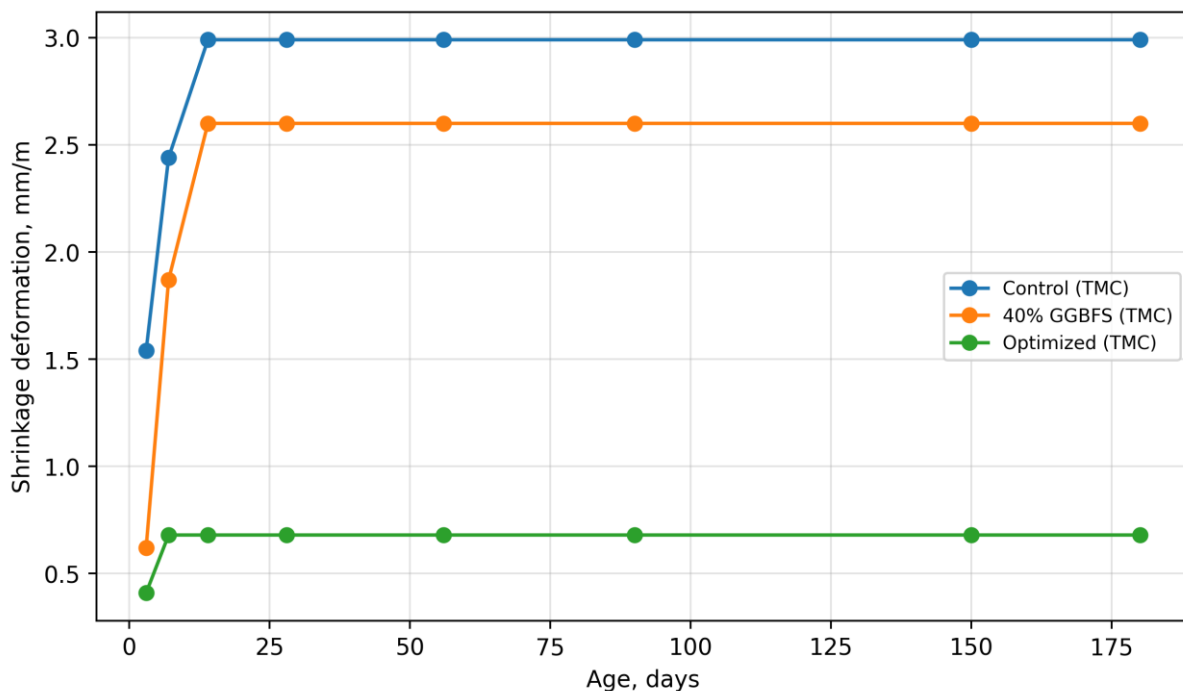


Figure 7. Shrinkage development of selected compositions after thermal-moisture curing.

**Microstructural evidence**

Microstructural observations support the macro-level performance results. The optimized composition is characterized by denser inter-pore partitions and a more continuous mineral matrix. The combined use of GGBFS-type slag, activated zeolite, metakaolin-gypsum

modifier and the AS accelerator promotes the formation of additional hydration products and reduces the number of weak zones caused by water separation or local foam collapse. The SEM image in Figure 8 illustrates the compact morphology of the optimized matrix.

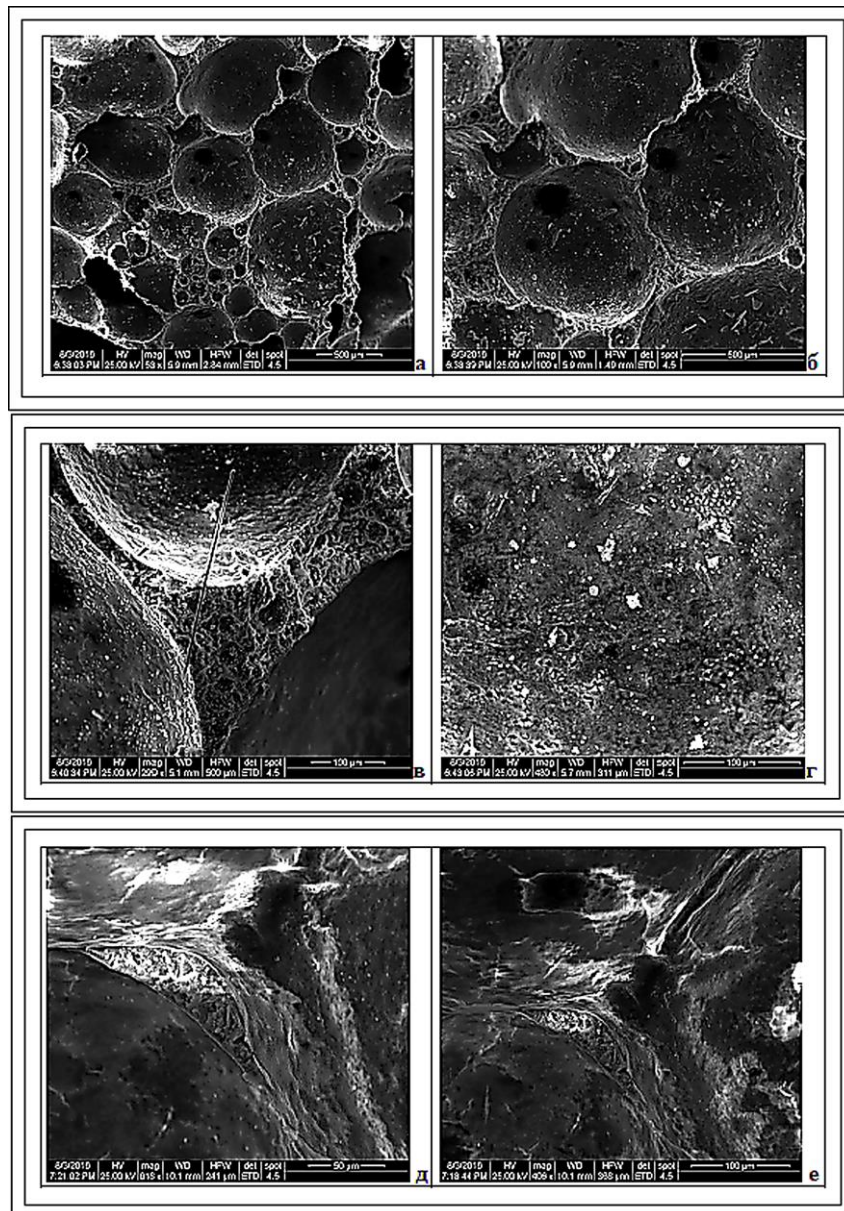


Figure 8. SEM image of the optimized D400 foam concrete matrix (composition 8, normal curing).

#### 4. Discussion

The results demonstrate that the improvement in foam concrete performance cannot be explained solely by lower water content. The system combines several mechanisms. First, Sika® ViscoCrete®-1095 disperses cement and mineral particles, allowing lower water demand at a stable consistency. Second, the GGBFS-type slag improves packing and contributes to additional hydrate formation. Third, activated zeolite and metakaolin provide fine aluminosilicate particles that fill microvoids and interact with calcium hydroxide. Fourth,

the AS accelerator shortens the period during which the fresh foam concrete remains structurally vulnerable.

The response-surface results show that the optimum is not located at the highest mineral addition level. This confirms that excessive fine mineral content can increase water demand and reduce the efficiency of the foam structure. The rational composition must therefore balance particle packing, chemical activity and rheological stability. The optimum around 30% GGBFS-type slag and 8% complex modifier satisfies this balance, producing both high strength and low thermal conductivity.

The decrease in shrinkage is particularly important for non-autoclaved foam concrete. Shrinkage in cellular

concretes is often associated with capillary water loss, weak inter-pore partitions and insufficient early matrix stiffness. The optimized composition reduces these risks through faster early structuring and a denser hydrate matrix. The resulting shrinkage level of 0.64-0.68 mm/m is considerably lower than that of the control composition and is compatible with more reliable enclosing elements.

From a practical viewpoint, the proposed system is relevant because it relies on components that can be adapted to local raw-material resources: metallurgical slag as a secondary mineral material, natural zeolite as an aluminosilicate microfiller, and an industrial PCE superplasticizer with stable properties. This combination makes it possible to develop non-autoclaved foam concrete with improved performance without requiring autoclave curing.

## 5. Conclusions

1. The rational dosage of the AS accelerator for the cement system was established in the range of 0.05-0.10% of cement mass; 0.07% was used in the optimized D400 foam concrete composition.
2. A combined mineral modification based on 30% GGBFS-type slag and 8% complex modifier (activated zeolite + MB-B-II-2) produced the best balance between strength, thermal conductivity and shrinkage.
3. The optimized D400 foam concrete reached 4.57 MPa after 28 days of normal curing and 3.35 MPa after thermal-moisture curing, while maintaining density within the D400 class.
4. Thermal conductivity decreased to 0.073-0.080 W/(m·°C), water absorption decreased to 17.3%, and the softening coefficient increased to 0.88, indicating improved hygrothermal stability.
5. Shrinkage deformation decreased to 0.64-0.68 mm/m, which confirms that dispersion optimization and early-structure stabilization effectively reduce volume-change risk in non-autoclaved foam concrete.
6. The proposed composition is suitable for further pilot-scale production and can be used as a technology-oriented basis for energy-efficient wall and thermal-insulation products in local construction practice.

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