

Research Article

Optimizing Non-Autoclaved Aerated Concrete with Technogenic Wastes: A Study of AOBT and BFW Effects

Akbermet Matyeva¹ , Elmira Sardarbekova^{2,*} , Makhavat Dzhusupova³ , Sodikzhon Melibaev¹ ,
Zhyldyz Asanalieva¹ 

¹ Institute of Construction and Innovative Technology, International University of Innovation Technologies, Bishkek, 720040, Kyrgyz Republic

² Department of Construction, Kyrgyz-Russian Slavic University, Bishkek, 720001, Kyrgyz Republic

³ Department of Production and Examination of Building Materials, Products and Structures, Kyrgyz State Technical University named after I. Razzakov, Bishkek, 720044, Kyrgyz Republic

*Corresponding Author: Elmira Sardarbekova, E-mail: sardarbekovaelmira669@gmail.com

Article Info	Abstract
Article History	The study aimed to develop an optimised composition for non-autoclaved aerated concrete using technogenic wastes and to evaluate their Effect on key physical and mechanical properties. Antimony ore beneficiation tailings (AOBT, 10-30%) and basalt fibre waste (BFW, 0-4%) were varied according to a two-factor central composite design. Tests were conducted for density, compressive strength, thermal conductivity, and drying shrinkage in accordance with State All-Union Standard procedures. Density ranged from 612 to 740 kg/m ³ , with the lowest values at 30% AOBT and 2% BFW, due to enhanced gas formation and reduced solid mass. Compressive strength reached 3.8 MPa in the same composition, reflecting a synergistic filler-fibre effect. Thermal conductivity (0.14-0.23 W/m·°C) decreased with increasing AOBT and optimal fibre content, while shrinkage (0.8-2.8 mm/m) was minimised when both components were increased, indicating spatial stabilisation. Regression analysis showed that AOBT primarily affected density and thermal conductivity, and BFW influenced shrinkage. The mixes are designed to comply with the relevant structural-insulating concrete standards for external load-bearing walls in low-rise construction, specifically meeting the requirements for strength class B3.5 as defined by ASTM C90 and ASTM C495. The optimal mix, which achieves a compressive strength of 2.6 to 3.8 MPa, is suitable for load-bearing walls and meets the minimum strength criteria for structural-insulating applications in low-rise buildings, ensuring both adequate mechanical performance and energy efficiency.
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1. Introduction

Modern construction imposes ever higher demands on the energy efficiency, environmental friendliness and resource intensity of building materials [1]. Under conditions of growing scarcity of natural resources and tighter environmental regulations, the use of secondary raw resources in the manufacture of

building products becomes particularly important. Aerated concrete, as one of the most sought-after light-weight concretes, offers a unique combination of low density, high thermal insulation, and sufficient load-bearing capacity, making it attractive for the construction of external walls [1]. However, traditional production technologies, especially those involving autoclaving, are associated with high energy consumption and high costs [1]. In this regard, the development of non-autoclaved variants of aerated concrete that combine environmental compatibility, energy efficiency and affordability is becoming increasingly relevant. The use of technogenic wastes, such as antimony ore beneficiation tailings (AOBT) and basalt fibre waste (BFW), is a promising approach for both disposing of hazardous materials and improving the functional performance of aerated concrete.

A key challenge in producing non-autoclaved aerated concrete is balancing low density with sufficient strength, particularly for structural-insulating materials [1]. A significant constraint is also the tendency of such concretes to drying shrinkage, which necessitates additional structural reinforcement and mix adjustments. An important feature of using technogenic mineral additives is their heterogeneous chemical composition, which may affect the mechanisms of gas formation, the development of the porous structure and the final physical and mechanical parameters of the material. The use of various mineral additives in the production of cellular concretes has been widely explored in recent studies. To improve the hardening kinetics of cellular concretes, Matyeva, et al. [1] investigated the function of finely dispersed silicate components in speeding up cement paste hydration. The technological issues of incorporating particular technogenic wastes, such as AOBT, and their potential as active gas-forming fillers, however, were not covered in their study; this work aims to close that gap.

Similarly, Abdykalykov, et al. [2] showed that adding reinforcing fibres, such as glass and polyolefin fibres, could improve the durability of cellular materials by reducing shrinkage. Their investigation did not examine the relative effects of organic versus inorganic fibres, nor their interactions with mineral components, such as AOBT, even though it confirmed the efficacy of three-dimensional reinforcement. Notably, despite their potential to significantly improve the material's mechanical properties, basalt fibres, renowned for their high heat resistance and stiffness, were not considered. Additionally, Sardarbekova [3] investigated the use of metallic ore tailings as micro-fillers in light-weight concretes, highlighting their capacity to reduce density through air entrainment. However, the ability to assess the materials' feasibility for load-bearing applications is limited by a lack of detailed analysis of their mechanical properties.

Zhou, et al. [4] made further progress by optimising the composition of light-weight concretes containing fly ash and slag using a central composite design. Although their method worked well for different first- and second-order factors, it lacked reinforcement elements and did not investigate the synergistic effects of combining fibres and fillers, which could have led to more significant material improvements. Similarly, Gu et al. [5] emphasised the need to combine active and inert components to improve the strength characteristics of light-weight concretes.

Shan, et al. [6] emphasised the significance of structural homogeneity by concentrating on the impact of porosity on the heat conductivity of light-weight concretes. The use of secondary resources, such as AOBT or BFW, which could have a substantial impact on the material's thermal properties, was not considered in their study. When adding reinforcing components, Peng et al. [7] noticed inconsistencies, which they attributed to intricate interactions among the mix's elements. Although they underlined the importance of a thorough approach, they made no specific recommendations for materials with significant dispersity, such as those containing ore tailings. Similarly, He et al. [8] examined how glass-industry waste affected concrete characteristics and concluded that particle morphology and introduction method were important factors. Unfortunately, their study did not use statistical analytical techniques and lacked a systematic approach to mixture optimisation, thereby limiting the accuracy of their findings.

Against the backdrop of the problems and gaps outlined, a systematic approach to studying the influence of AOBT and BFW on the properties of non-autoclaved aerated concrete is particularly significant. The research aimed to determine the optimal composition of non-autoclaved aerated concrete using AOBT and BFW that ensures the required levels of density, strength, thermal insulation and shrinkage resistance. The objectives of the study included varying the content of components according to the experimental plan, testing specimens for key physical and mechanical indicators and mathematically processing the results to identify the dominant factors.

2. Materials and Methods

AOBT and BFW were preliminarily characterised to ensure reproducibility, given the known variability of technogenic materials. AOBT was collected from the tailings storage facility of the Kadamjay antimony plant (southern Kyrgyzstan) and represents fine-grained (<0.16 mm) waste formed during gravity-flotation processing of antimony ores. BFW originated from industrial production losses during

continuous basalt fibre manufacturing from basalts of the Sulu-Terek deposit (Kyrgyzstan) and consisted of short, discontinuous fibre fragments.

The chemical composition of AOBT and BFW was determined by X-ray fluorescence (XRF) analysis on dried and finely ground samples ($<75\ \mu\text{m}$). As is typical of siliceous-aluminosilicate beneficiation tailings, silica (SiO_2) and alumina (Al_2O_3) dominated AOBT, with trace levels of iron oxide (FeO_3), calcium oxide (CaO), and magnesium oxide (MgO). As a result of its magmatic origin, BFW, on the other hand, showed a basaltic oxide composition rich in silica (SiO_2), alumina (Al_2O_3), calcium oxide (CaO), magnesium oxide (MgO), and iron oxide (Fe_2O_3). X-ray diffraction (XRD, Cu $K\alpha$ radiation, $2\theta=5-70^\circ$) was used to determine the mineralogical composition. It revealed that BFW had a predominantly amorphous structure typical of fast-quenched basalt fibres, whereas AOBT was composed primarily of crystalline quartz and feldspar phases, with a small amorphous component. These properties support the use of BFW as a chemically inert, physically reinforcing component in non-autoclaved aerated concrete and AOBT as a reactive siliceous microfiller that affects gas formation and structure development.

Table 1. Mix proportions of experimental mixtures for non-autoclaved aerated concrete

No.	AOBT, %	BFW, %	Cement, kg/m^3	Lime, kg/m^3	Aluminium powder, g	Calcium chloride, %
1	10	0	300	80	0.07	1
2	30	0	300	80	0.07	1
3	10	4	300	80	0.07	1
4	30	4	300	80	0.07	1
5	30	2	300	80	0.07	1
6	10	2	300	80	0.07	1
7	20	4	300	80	0.07	1
8	20	0	300	80	0.07	1
9	20	2	300	80	0.07	1

Note: A mix with 0% AOBT was not considered because AOBT is a siliceous material that contributes to the overall porosity of the mix, primarily through its interaction with the hydration products of lime and cement, which create a highly alkaline environment that facilitates the generation of hydrogen gas when reacting with aluminium powder. AOBT's role in enhancing porosity is more closely related to its influence on the material's rheology, nucleation, and microfiller effects than to its direct gas-forming role. In contrast, BFW serves only as a reinforcing modifier, so a 0% BFW mix was included as a reference to assess its isolated Effect. The aluminium powder is given in grams per kg of binder.

The constant components of the formulations were Portland cement grade M400 D20 according to State All-Union Standard (GOST) 31108-2020 [9], hydrated lime, aluminium powder and calcium chloride.

The detailed proportions are provided in Table 1. Components were pre-dried to constant mass at 105 °C, then weighed to ± 0.01 g and mixed in an IKA RW 20 digital laboratory mixer (Germany) until a homogeneous mass was achieved. Mixing water was added in a quantity ensuring standard workability of the mix, with a water-to-binder ratio of 135 kg/m³. The material is non-autoclaved aerated concrete, not mortar.

The absence of coarse aggregate is intentional and inherent to aerated concrete technology, where a homogeneous fine-grained matrix is required to ensure uniform gas formation and stable pore structure; coarse aggregates would disrupt porosity and lead to structural instability. Since all of the solid components were used in a finely dispersed form compatible with the design of an aerated concrete mix, sieve analysis was not applicable, as hydrated lime was used as a reactive mineral rather than an aggregate.

Prepared mixes were cast into metal moulds measuring 100×100×100 mm and 40×40×160 mm (Figures 1a and 1b), subjected to light vibration compaction and conditioned under moist curing at 20±2°C and relative humidity not less than 95% for 24 hours. Cubes of 100×100×100 mm were used to ensure representative strength and shrinkage measurements. In total, 9 series of 6 specimens each were produced, ensuring the reliability of the data obtained. After demolding, specimens were stored under laboratory conditions at 20±2°C and 60±5% relative humidity for 28 days. Bulk density was determined according to GOST 25485-2019 [10], and compressive strength was determined according to GOST 10180-2012 [11] using a Controls Autamax 5 hydraulic press (Italy) (Figure 1c). Thermal conductivity was measured using an ISOMET 2114 device (Slovakia) (Figure 1d), and drying shrinkage was measured according to GOST 30744-2001 [12]. Moisture content and water absorption were additionally determined in accordance with GOST 12730.2-2020 [13] and GOST 12730.3-2020 [14], respectively.

To study the Effect of quantitative factors on the properties of aerated concrete, a two-factor central composite design (second order) was employed, varying the AOBT content (x_1) and the BFW content (x_2). In total, nine mix combinations were implemented, including the design centre, axial and extreme points. Mathematical processing of the experimental data was performed in the STATISTICA 13 software environment (USA) using regression analysis and the construction of second-order polynomial models. Model adequacy was assessed using Cochran's and Fisher's criteria, and the significance of coefficients was assessed using Student's t-test at the $p \leq 0.05$ significance level. Nomograms and three-dimensional response surface plots were used to visualise factor effects.



Figure 1. The equipment used in the study

3. Results

The results of the experiment to determine the bulk density of non-autoclaved aerated concrete while varying the contents of AOBT and BFW are presented in Table 2. The visual changes are shown in Figure 2. As shown in the data, density varied widely, with a clear dependence on the proportions of the technogenic components. AOBT plays a primary role in influencing the bulk density of non-autoclaved aerated concrete. Due to the reaction between aluminium powder and the highly alkaline environment created by the hydration products of lime and cement, which generates hydrogen gas, the density significantly decreases as the AOBT percentage increases. According to the findings, mixes containing 30% AOBT have the lowest density (612 kg/m^3), which is explained by increased gas production and decreased solid-phase concentration. To achieve the requisite light-weight quality in structural-insulating concrete, which is critical for reducing building energy consumption, this reduced density is essential. However, the impact of adding BFW on density is less pronounced. BFW stabilises the pore structure through physical

reinforcement, forming a three-dimensional fibre network that limits pore coalescence and excessive expansion during gas release. As shown by the comparison of mixes 7-9, BFW also indirectly affects density and thermal conductivity by modifying pore geometry, indicating that its influence is structural rather than chemical and not negligible. The maximum value of density (740 kg/m^3) was obtained at the minimum AOBT content (10%) and an intermediate BFW level (2%), due to a higher share of dense mineral constituents. Such variation in density suggests the possibility of effectively adjusting formulation parameters to achieve the required structural-insulating aerated concrete class.

Table 2. Determination of the bulk density of aerated concrete for different mixes

No.	AOBT, %	BFW, %	Bulk density ρ , kg/m^3
1	10	0	728
2	30	0	622
3	10	4	669
4	30	4	623
5	30	2	612
6	10	2	740
7	20	4	674
8	20	0	634
9	20	2	653

Note: Mix 9 exhibits a higher density than Mix 5 because its lower AOBT content reduces gas formation and the basalt fibres restrict pore expansion, leading to partial matrix densification. In contrast, the higher AOBT content and optimal fibre dosage in Mix 5 promote more intensive pore formation and a lighter, more uniform cellular structure.

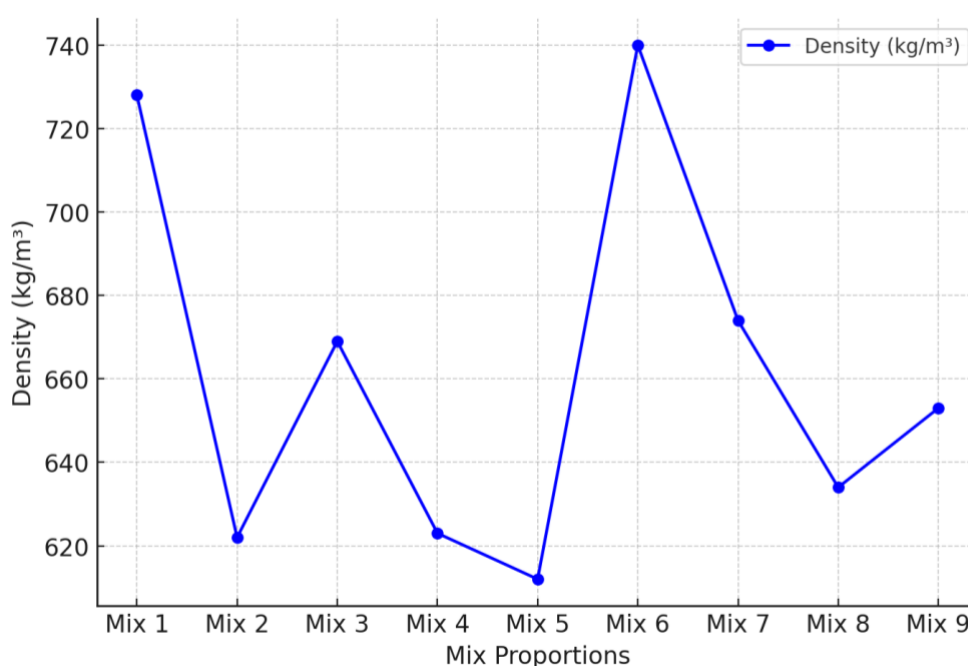


Figure 2. Variation of bulk density across mixes with different AOBT and BFW contents

The influence of AOBT content (x_1) and BFW content (x_2) on the bulk density of non-autoclaved aerated concrete was analysed using a second-order polynomial regression model derived from the central composite experimental design. Within the investigated domain, bulk density (ρ , kg/m³) can be expressed as Equation (1):

$$\rho = 660.3 - 46.7x_1 + 12.0x_1^2 - 3.0x_2 - 10.0x_2^2 + 15.0x_1x_2, \quad (1)$$

where the coded variables x_1 and x_2 represent the BFW content (0-4%) and AOBT content (10-30%), respectively. Only these factors, together with the curing and testing conditions, make Equation (1) valid; extrapolation outside of these parameters is not warranted. According to the regression coefficients, the primary factor controlling density change is AOBT content. Due to its siliceous nature and its capacity to enhance gas production in the presence of aluminium powder, which encourages the formation of a more porous cellular structure, the negative linear coefficient (-46.7) indicates a systematic reduction in density with increasing AOBT.

The next most significant factor, the basalt fibre content, has a much smaller effect, with a linear coefficient of -3.0. This indicates that the introduction of BFW alone does not cause substantial changes in density, but it does exert an additional stabilising effect. The interaction term x_1x_2 (+15.0) is also important in the model, reflecting a positive interaction between AOBT and fibres that "smooths" the density-reducing Effect when both components are present, as fibres limit excessive pore expansion at high gas contents.

The quadratic terms are of particular interest: x_1^2 (+12.0) indicates a critical point beyond which further increases in AOBT may no longer reduce, and may even slightly raise, density due to structure densification; x_2^2 (-10.0) suggests an optimal fiber interval, outside of which negative effects may occur, likely due to fiber agglomeration and reduced efficiency of spatial distribution.

Valuable visual confirmation is provided in the nomogram (Figure 3), which shows the response surface for density as a function of x_1 and x_2 . It can be seen that at zero fibre content ($x_2 = -1$) and increasing AOBT from 10 to 30%, density decreases from 720 to 600 kg/m³ (about 20%), confirming the model's linear trend. Meanwhile, at a constant AOBT level of 10% and increasing BFW to 4% ($x_2 = +1$), density decreases by only 30 kg/m³, indicating a moderate influence of the reinforcing component. The most balanced density values, in the range 620-640 kg/m³, are observed with 25-30% AOBT and 2-3% fibers.

Thus, the analysis shows that density control in non-autoclaved aerated concrete is feasible by varying the proportions of AOBT and BFW. The maximum density reduction is achieved at high AOBT content

and a moderate fibre level, ensuring compliance with the GOST requirements for structural-insulating cellular concrete.

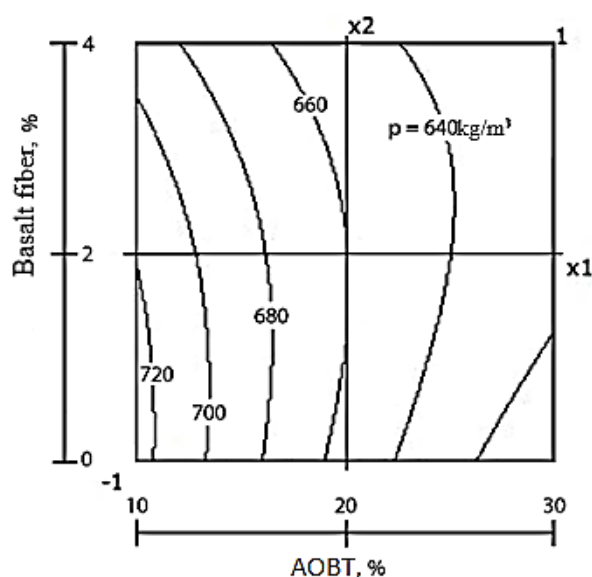


Figure 3. Nomogram of aerated concrete density $\rho = f(x_1, x_2)$

Compressive strength of the aerated concrete specimens was assessed at 28 days, the standard age for determining design strength per GOST. The data are given in Table 3, spanning 2.6 to 3.8 MPa. The lowest strengths were recorded at the lowest AOBT content with no reinforcing component, due to a weak structural matrix with insufficient mineralisation (Figure 4). Because of its high silica and alumina content, AOBT helps form a more hydrated, mineralised structure, which increases overall strength. However, the interaction with BFW also affects strength. 30% AOBT and 2% BFW produced the highest compressive strength (3.8 MPa), suggesting that the mineral filler (AOBT) and reinforcing fibres (BFW) work in unison. The inclusion of BFW helps disperse stress throughout the material, reducing microcrack formation and enhancing resistance to deformation, even though AOBT alone cannot provide adequate structural integrity. The optimal BFW content for compressive strength is 2%, as it maximises synergy between AOBT and BFW by supporting the matrix without inducing fibre aggregation. As evidenced by the maximum compressive strength of 3.8 MPa attained with 30% AOBT and 2% BFW, this interaction improves mineralisation and bonding.

For cellular concretes, the apparent increase in compressive strength seen in Figure 4 with decreasing density does not conflict with known material behaviour. Fibre reinforcement and reactive mineral fillers alter the mechanism governing strength development, even though density remains the primary determining factor in conventional aerated concrete. In the current work, basalt fibres stabilise pore walls and bridge

microcracks, thereby improving load transmission efficiency, while AOBT helps create a finer, more uniform pore structure and promotes greater hydrate formation. For fibre-reinforced aerated concretes, similar departures from a monotonic density-strength relationship have been documented in the literature, where increased strength at comparable or lower densities is enabled by improved microstructural quality. From a regulatory standpoint, ASTM C1693 [15] for cellular concrete products emphasises minimum strength criteria rather than fixed density-strength proportionality, and every mix in this study falls within the permissible performance domain for structural-insulating applications.

Table 3. Compressive strength of non-autoclaved aerated concrete at 28 days

No.	AOBT, %	BFW, %	Compressive strength $R_{c,28}$, MPa
1	10	0	2.6
2	30	0	2.8
3	10	4	2.9
4	30	4	3.2
5	30	2	3.8
6	10	2	2.7
7	20	4	3.1
8	20	0	2.8
9	20	2	3.0

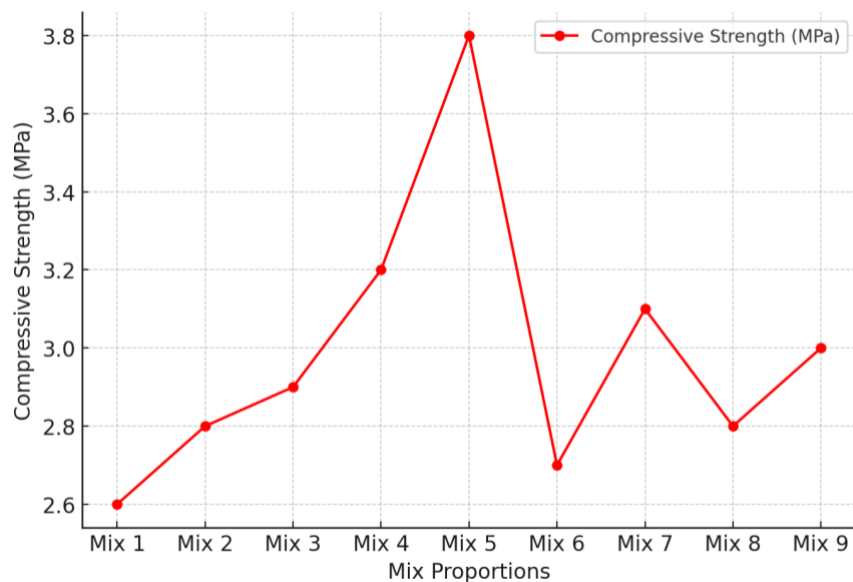


Figure 4. Compressive strength development across mix variants

The results in Table 3 may seem low at first glance. However, since the material is intended for structural-insulating applications rather than high load-bearing ones, this strength is in line with its intended use. Aerated concrete with a reduced AOBT content and no fibre reinforcement exhibited the lowest

compressive strengths, indicating a weaker structural matrix. However, a mixture of 30% AOBT and 2% basalt fibres yielded the highest compressive strength (3.8 MPa), demonstrating the synergistic Effect of the mineral filler and fibre reinforcement, thereby enhancing the material's structural integrity. In practice, load-bearing walls for low-rise buildings that fall under the B2-B3.5 strength class must have a strength of 3.0 MPa or greater.

The Effect of AOBT content (x_1) and BFW content (x_2) on the 28-day compressive strength of non-autoclaved aerated concrete was evaluated using a second-order polynomial regression model that accounts for linear, quadratic, and interaction effects. Within the experimental domain, the 28-day compressive strength $R_{c,28}$ (MPa) is described by Equation (2):

$$Y_2(R_{c,28}) = 3.11 + 0.27x_1 + 0.03x_1^2 + 0.17x_2 - 0.27x_2^2 + 0.03x_1x_2, \quad (2)$$

where the coded variables x_1 and x_2 denote AOBT content in the 10-30% range and BFW content in the 0-4% range, respectively. Extrapolation outside of this range is not relevant; Equation (2) is only acceptable within these factor limitations and under the curing and testing conditions. The linear Effect of AOBT (+0.27) is the dominant contributor to strength development, according to the regression coefficient analysis. This confirms that increasing the proportion of siliceous mineral filler promotes hydration, enhances microstructural densification, and results in a stronger cementitious matrix. AOBT's high silica, alumina, and iron oxide concentrations promote further C-S-H gel formation and pore-space mineralisation, thereby enhancing the material's mechanical performance.

The reinforcing component, basalt fibre, has a significant but less pronounced effect. The linear coefficient (+0.17) reflects strength gains from three-dimensional reinforcement, in which fibres limit microcrack development and increase resistance to deformation. However, the quadratic coefficient for x_2 is -0.27, indicating reduced effectiveness at excessive fibre contents, possibly due to agglomeration and non-uniform distribution, creating local heterogeneities where stresses concentrate, and micro-failure can initiate.

The combined action of both factors is reflected in the positive interaction coefficient $x_1x_2 = +0.03$, indicating a mildly synergistic effect, especially at optimal levels of both components. This can be explained by the mutual enhancement of structural densification/mineralisation (via AOBT) and crack resistance (via fibres).

Visualisation is provided in Figure 5. The nomogram shows strength development as a function of x_1 and x_2 . With no fibres ($x_2=-1$) and AOBT increasing from 10 to 30%, strength rises from 2.6 to 3.0 MPa ($\sim 13\%$). With 2-3% fibers ($x_2=0\ldots 0.5$) and AOBT at 25-30%, strength increases more markedly to 3.4-3.8 MPa, evidencing comprehensive strengthening. Even at the extremes, 30% AOBT and 4% BFW, strength remains high at about 3.3 MPa, $\sim 25\%$ above the initial values. Figure 5 shows a continuous response surface rather than discrete mix points. Therefore, at AOBT=15%, the BFW ratio should be selected using the optimisation criterion of interest or the nearest tested BFW level predicted by the model, rather than by direct visual reading.

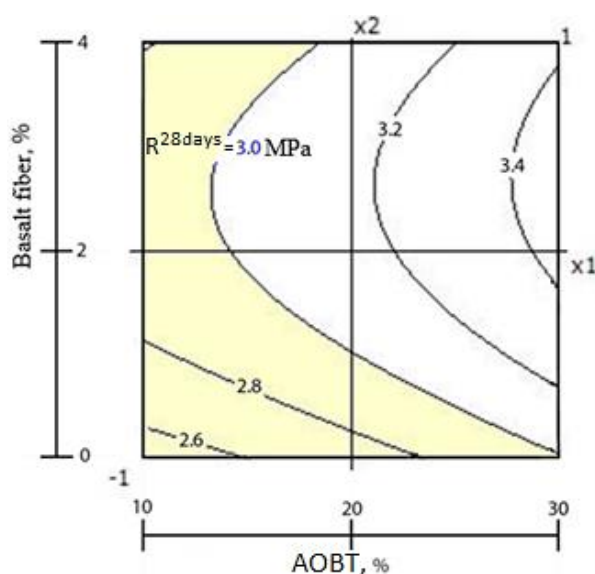


Figure 5. Nomogram of aerated concrete strength after 28 days, $Y_2 (R_{28days}) = f(x_1, x_2)$

The highest strengths are recorded in the zone ($x_1=1, x_2=0\ldots 0.5$), which in natural units corresponds to 30% AOBT and 2-3% BFW. This mix corresponds to strength class B3.5 and can be classified as structural-insulating concrete suitable for load-bearing walls in low-rise buildings. Thus, optimising the ratio between AOBT and BFW allows targeted control of strength while ensuring economy through the use of technogenic raw materials and compliance with strength standards.

To substantiate the optimisation claims derived from the mechanical and regression analyses, scanning electron microscopy (SEM) images were provided to demonstrate the microstructural features of the optimised non-autoclaved aerated concrete compositions (Figure 6). Since these parameters control the development of strength and deformation resistance in cellular cementitious systems, special attention was given to the morphology of the calcium silicate hydrate (C-S-H) gel and the properties of the interface transition zone (ITZ).

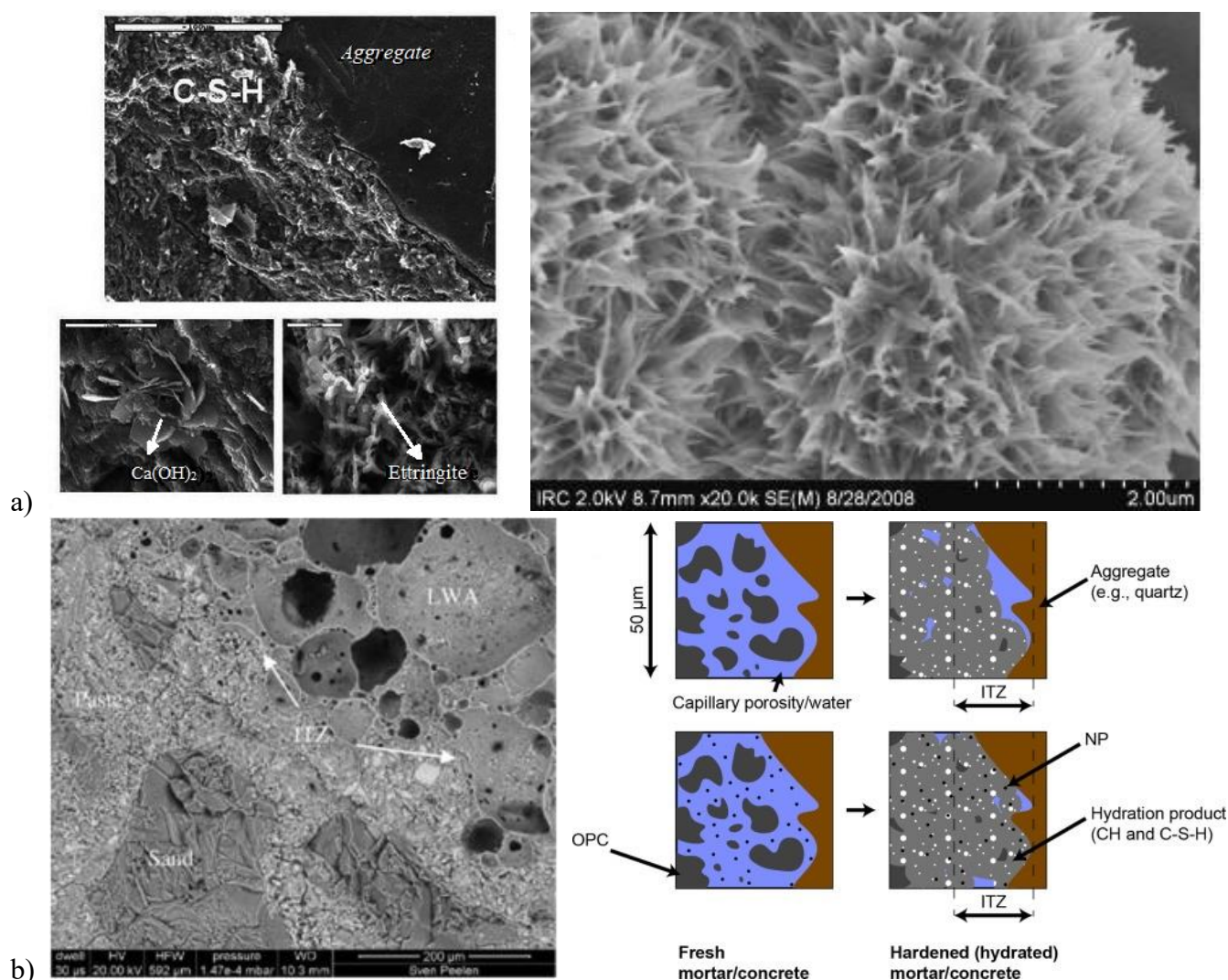


Figure 6. SEM micrographs of optimised non-autoclaved aerated concrete: (a) dense C-S-H gel structure formed in the cementitious matrix due to the presence of technogenic siliceous components; (b) compact ITZ between basalt fibre waste and the matrix, demonstrating enhanced mechanical interlocking and fibre-matrix bonding

The impact of technogenic components on hydration processes and interfacial bonding under ambient curing conditions is demonstrated by the SEM images shown in Figure 6. Compared with traditional non-autoclaved matrices, the cementitious matrix in systems containing antimony ore beneficiation tailings forms a thick, fine-textured C-S-H gel that forms a continuous network within the pore walls, indicating accelerated mineralisation. At the same time, a compact, well-integrated ITZ with basalt fibre waste is linked to hydration products that adhere tightly to the fibre surface, promoting efficient stress transfer and mechanical interlocking. Collectively, these microstructural features indicate that the observed optimisation is not solely the result of statistical correlations but is also supported by enhanced matrix densification and fibre-matrix interactions.

Thermal conductivity was assessed to identify mixes with improved insulation. According to Table 4, λ ranged from 0.14 to 0.23 W/m $\cdot$ °C. By encouraging gas production and boosting porosity, which results in a closed-cell structure that inhibits heat transfer, AOBT has a major impact on thermal conductivity. The experiment shows that mixes containing 30% AOBT have the lowest thermal conductivity (0.14 W/m $\cdot$ °C), whereas higher porosity breaks down thermal bridges and improves insulation (Figure 7). To balance porosity and heat resistance, the AOBT content must be controlled; 30% AOBT offers the best insulation. Similarly, BFW has a mild impact on thermal conductivity. By stabilising the pore structure and reducing convective air movement, adding basalt fibres (2-4%) lowers thermal conductivity. On the other hand, fibre aggregation due to excessive fibre content (>3%) might disrupt the pore structure and increase thermal conductivity. A compromise between reducing heat conductivity and enhancing mechanical properties is achieved at the optimal BFW level of 2%.

Table 4. Thermal conductivity of non-autoclaved aerated concrete for different mixes

No.	AOBT, %	BFW, %	Thermal conductivity λ , W/m $\cdot$ °C
1	10	0	0.19
2	30	0	0.15
3	10	4	0.16
4	30	4	0.15
5	30	2	0.14
6	10	2	0.23
7	20	4	0.17
8	20	0	0.15
9	20	2	0.16

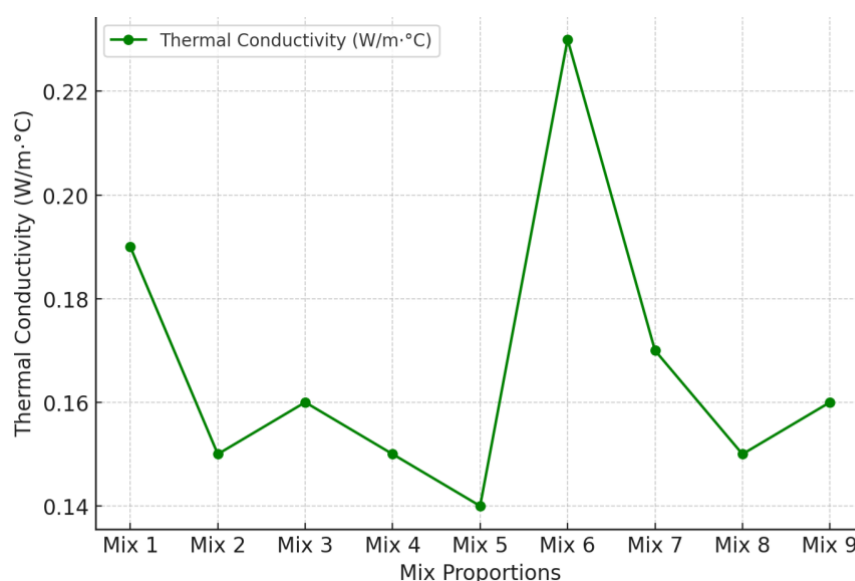


Figure 7. Thermal conductivity as a function of AOBT and BFW proportions

The influence of AOBT content (x_1) and BFW content (x_2) on the thermal conductivity of non-autoclaved aerated concrete was analysed using a second-order polynomial regression model derived from the applied central composite design. Within the investigated factor space, thermal conductivity λ ($\text{W/m}\cdot^\circ\text{C}$) can be expressed as Equation (3):

$$Y_3(\lambda) = 0.17 - 0.023x_1 + 0.01x_1^2 - 0.002x_2 - 0.015x_2^2 + 0.008x_1x_2, \quad (3)$$

where x_1 and x_2 are coded variables corresponding to AOBT content in the range of 10-30% and BFW content in the range of 0-4%, respectively. Extrapolation beyond this domain is not warranted; Equation (3) is only applicable within these bounds and under the curing and testing conditions. The AOBT content is the primary factor affecting thermal conductivity, according to the regression coefficients. The creation of a more uniform closed-cell system and the refining of pore structure are responsible for the systematic decrease in λ with increasing AOBT, as indicated by the negative linear coefficient (-0.023). By reducing thermal bridges between solid phases and increasing the volume fraction of trapped air, this microstructure impedes heat transfer. Additionally, AOBT's siliceous nature promotes micro-porosity by interacting with binder hydration products.

The quadratic term x_1^2 (+0.01) confirms a saturation effect at high AOBT contents, where further increases no longer reduce λ and may even raise it due to densification. Thus, there is a rational AOBT limit, around 30%, at which minimum λ is achieved without compromising other properties.

The influence of basalt fibre on λ is much weaker (linear -0.002), but its quadratic term x_2^2 (-0.015) is more significant, indicating an optimal dosage at which fibres are most effectively dispersed without disrupting structural integrity. Excess fibre (>3-4%) may lead to clumping and channel formation, worsening thermal performance. At ~2%, fibres stabilise the pore geometry and hinder convective air movement within the cells, thereby further lowering λ .

The interaction term $x_1x_2 = +0.008$ shows a weak positive link, suggesting that the simultaneous presence of AOBT and fibres may slightly temper excessive reductions in λ in highly porous mixes, interpreted as fibre-mediated stabilisation that prevents structural degradation at very high gas contents.

Figure 8 shows the region of effective mixes with $\lambda \leq 0.14 \text{ W/m}\cdot^\circ\text{C}$. A clear 43% decrease – from 0.20 to 0.14 $\text{W/m}\cdot^\circ\text{C}$ – is achieved by increasing AOBT from 10 to 30% without fibres, underscoring the key role of the mineral filler with siliceous content in insulation.

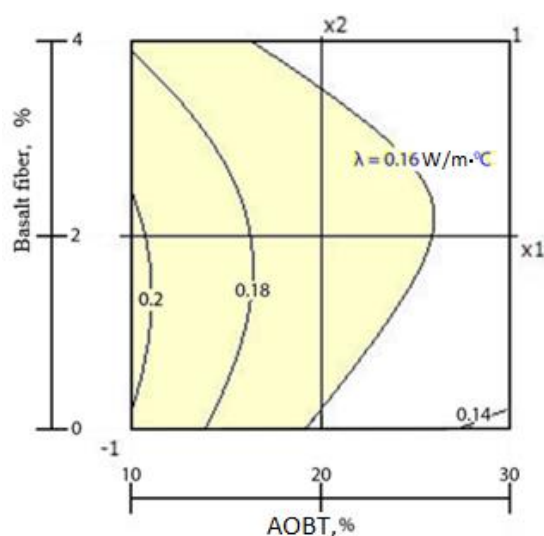


Figure 8. Nomogram of aerated concrete thermal conductivity, $Y_3(\lambda)=f(x_1, x_2)$

With 20% AOBT and 4% fibers, λ drops from 0.17 to 0.16 W/m·°C – a modest but stable improvement. The optimal zone, combining minimum λ and balanced mechanical properties, is 30% AOBT with 2% BFW, where $\lambda = 0.14$ W/m·°C. This confirms that effective mix design requires not merely increasing porosity but balancing pore-forming and reinforcing components. In summary, the lowest λ values are observed with 30% AOBT and 2% BFW, enabling classification as structural-insulating cellular concretes suitable for external walls that meet energy-efficiency requirements.

Figure 9 presents the relationship between bulk density and thermal conductivity, where individual markers represent experimental data points, and the connecting line illustrates the empirical trend obtained by ordering the mixes by increasing density.

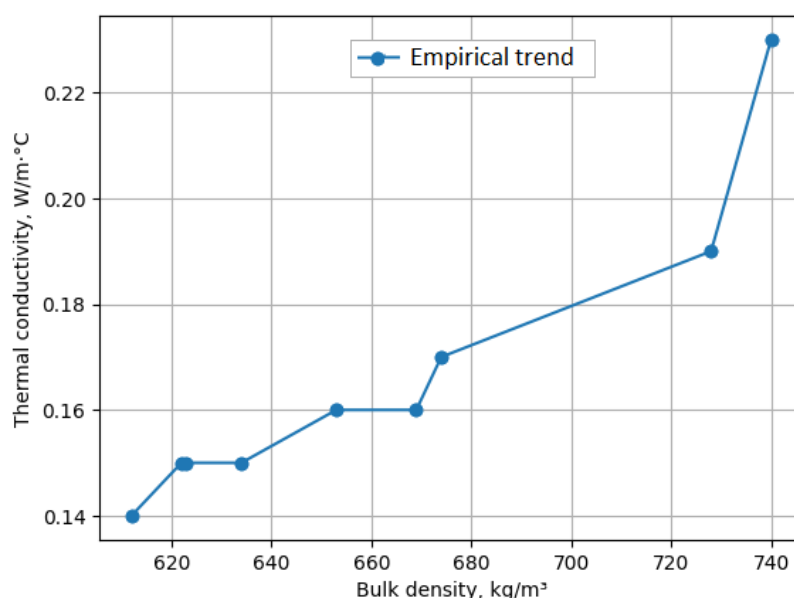


Figure 9. Density-thermal conductivity relationship

This representation highlights the gradual, continuous nature of thermal conductivity's density dependence, without implying a fitted regression model. The absence of abrupt deviations along the trend indicates that the inclusion of basalt fibre waste does not cause a disproportionate increase in thermal conductivity, thereby preserving the suitability of the material for use as thermal insulation blocks.

Drying shrinkage is a critical parameter for cellular concretes, as it directly affects service reliability and durability. According to Table 5, shrinkage varied from 0.8 to 2.8 mm/m depending on the AOBT-BFW ratio. By producing a more homogeneous, denser pore structure, AOBT's high porosity and reactivity help mitigate shrinkage by reducing capillary activity and moisture evaporation. According to the experimental results, 30% AOBT paired with 2-4% BFW produces the lowest shrinkage values (0.8 mm/m), suggesting that AOBT aids in lowering internal tensions that may otherwise cause shrinkage (Figure 10). However, additional shrinkage reductions become limited at greater AOBT concentrations, indicating a threshold beyond which AOBT's efficacy in reducing shrinkage declines.

Table 5. Drying shrinkage of non-autoclaved aerated concrete versus mix composition

No.	AOBT, %	BFW, %	Shrinkage $\varepsilon_{(sh)}$, mm/m
1	10	0	2.8
2	30	0	2.2
3	10	4	1.8
4	30	4	1.0
5	30	2	0.8
6	10	2	2.0
7	20	4	1.3
8	20	0	1.6
9	20	2	1.4

Additionally, by providing structural reinforcement and limiting excessive deformation during drying, BFW significantly reduces drying shrinkage. When both AOBT and BFW are operating at ideal levels, shrinkage decreases from 2.8 mm/m to 0.8 mm/m, resulting in the lowest shrinkage. During the drying process, excessive movement inside the concrete is prevented by the 3D network of basalt fibres, which helps preserve the material's structural integrity. Overall, all values complied with GOST (≤ 3 mm/m), confirming the practical suitability of the studied mixes.

The Effect of AOBT content (x_1) and BFW content (x_2) on the drying shrinkage of non-autoclaved aerated concrete was analysed using a second-order polynomial regression model developed within the

framework of the applied experimental design. Within the investigated factor domain, drying shrinkage $\varepsilon_{(sh)}$ (mm/m) can be expressed as Equation (4):

$$Y_4(\varepsilon_{(sh)}) = 1.178 - 0.433x_1 + 0.333x_1^2 - 0.417x_2 + 0.383x_2^2 - 0.05x_1x_2. \quad (4)$$

Only within these factor limitations and under the curing and testing conditions is Equation (4) valid; extrapolation beyond this domain is not relevant. The negative regression coefficients indicate that both AOBT and BFW have a significant stabilising effect on volumetric deformation, validating their role in reducing drying shrinkage across the examined composition range.

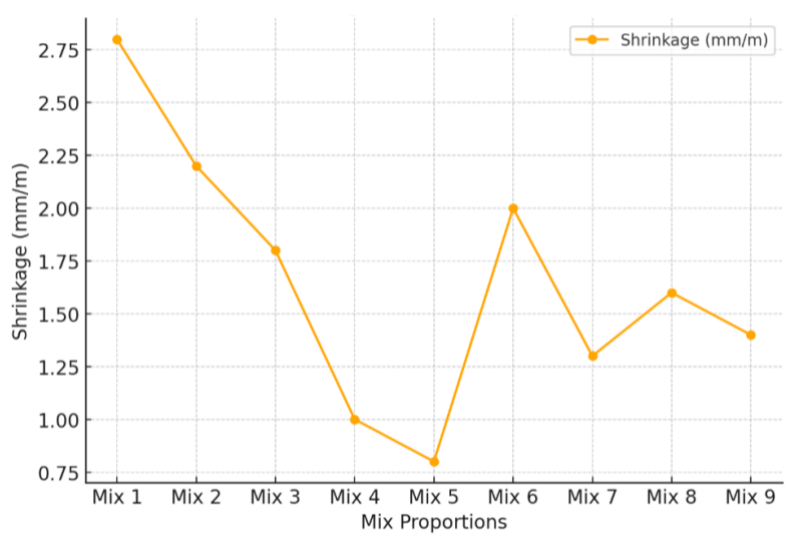


Figure 10. Drying shrinkage response to variations in AOBT and BFW

The largest Effect is the linear coefficient for x_1 (-0.433), indicating a substantial reduction in shrinkage as AOBT increases. The mineral component, rich in silica, densifies the structure and reduces capillary activity by forming a highly mineralised microstructure, thereby lowering moisture evaporation from the pore structure – the main cause of shrinkage in cellular concretes.

To mitigate the natural tendency of non-autoclaved aerated concrete to undergo drying shrinkage, a comparative analysis of shrinkage development over time was conducted (Table 6). It is feasible to analyse not only the initial deformation behaviour but also the material's stability during extended curing and moisture loss by including measurements at 28 and 90 days. This is crucial for evaluating service performance.

The comparisons in Table 6 show that technogenic mineral and fibre components greatly influence drying shrinkage over time. Mixtures with increasing proportions of antimony ore beneficiation tailings and mild basalt fibre show less shrinkage at later ages, indicating pore structure stabilisation and

suppression of progressive deformation. Composites with lower levels of these components have a stronger time-dependent reaction, proving that rational mix design can overcome non-autoclaved aerated concrete's main drawback.

Table 6. Drying shrinkage of non-autoclaved aerated concrete at 28 and 90 days

No.	AOBT, %	BFW, %	Drying shrinkage at 28 days, mm/m	Drying shrinkage at 90 days, mm/m
1	10	0	2.8	3.1
2	30	0	2.2	2.4
3	10	4	1.8	2.0
4	30	4	1.0	1.2
5	30	2	0.8	0.9
6	10	2	2.0	2.3
7	20	4	1.3	1.5
8	20	0	1.6	1.9
9	20	2	1.4	1.6

Basalt fibre has a similarly significant influence: the linear coefficient for x_2 is -0.417, almost equal to that of AOBT, confirming that fibres effectively restrain free deformation through three-dimensional reinforcement. Fibres create a framework that maintains the material's shape during drying, thus reducing shrinkage. However, the quadratic terms $x_1^2 = +0.333$ and $x_2^2 = +0.383$ indicate non-linear effects, whereby excessive concentrations (especially of fibres) can diminish benefits, as overly dense structures or fibre agglomeration can hinder uniform moisture distribution and create local stress concentrations. The negative interaction term $x_1x_2 = -0.05$ indicates a synergistic reduction in shrinkage when both components are increased together, most evident at high levels of both, where the minimum of 0.8 mm/m is achieved.

Figure 11 clearly shows the optimum region of formulations corresponding to minimal shrinkage. Increasing AOBT from 10 to 30% with no fibres ($x_2 = -1$) reduces shrinkage from 2.4 to 1.8 mm/m – a moderate effect. A more pronounced reduction occurs when fibres rise from 0 to 4% at a constant 10% AOBT: shrinkage decreases from 2.4 to 1.8 mm/m. The greatest Effect is achieved by combining high levels of both components: at 30% AOBT and 3-4% BFW, shrinkage decreases to 0.8-1.0 mm/m, about 3.5 times lower than the baseline mixes. These formulations are therefore especially attractive for structural materials with high geometric stability.

It is important to note that all tested compositions meet the requirements of GOST, which stipulate that the permissible level of shrinkage during drying should not exceed 3 mm/m. The studied values range

from 0.8 to 2.8 mm/m, confirming the high reliability of the formulations in terms of shrinkage deformation. In addition, a comparative assessment against relevant ASTM standards (Table 7) demonstrates that the observed shrinkage, density, strength, and thermal conductivity values are also within internationally accepted limits for light-weight and thermal-insulation concrete materials, confirming the global acceptability of the obtained reductions.

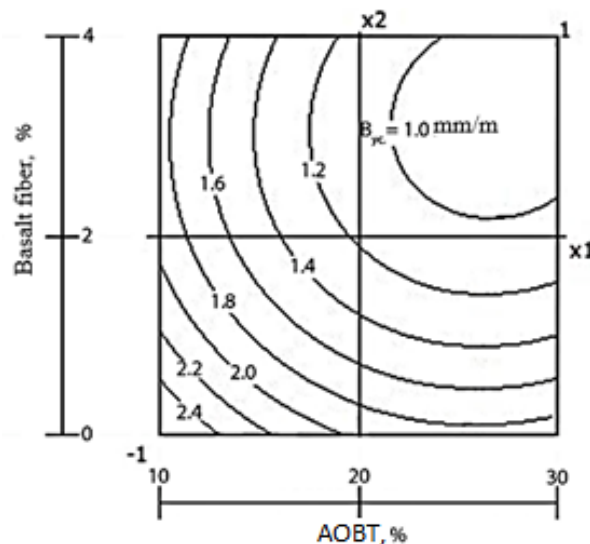


Figure 11. Nomogram of drying shrinkage of aerated concrete, $Y_4(\varepsilon_{sh})=f(x_1, x_2)$

Table 7. Compliance of physical and thermophysical properties of non-autoclaved aerated concrete with ASTM standards

Property	Experimental range	ASTM acceptable range/requirement	Compliance assessment	Relevant ASTM standard
Bulk density	612-740	Typically, 400-800 for light-weight insulating and structural light-weight concrete masonry units	Fully compliant; values fall within the ASTM-defined light-weight range	ASTM C1693[15]; ASTM C90[16]
Compressive strength	2.6-3.8	≥ 2.5 for non-loadbearing and ≥ 3.0 for loadbearing light-weight masonry units	Compliant for structural-insulating applications at optimal compositions	ASTM C90 [16]; ASTM C495 [17]
Thermal conductivity	0.14-0.23	≤ 0.25 for thermal insulation concrete blocks	Fully compliant; insulation performance preserved	ASTM C177[18]; ASTM C518 [19]
Drying shrinkage (28 days)	0.8-2.8	≤ 3.0 (recommended upper limit for cellular and light-weight concretes)	Compliant; all mixes below threshold	ASTM C157/C157M [20]
Drying shrinkage (90 days)	0.9-3.1	≤ 3.5 (long-term shrinkage limit for light-weight concrete)	Marginal-to-fully compliant depending on composition; optimised mixes are fully compliant	ASTM C157/C157M [20]

Thus, it was found that simultaneous variation of the AOBT and basalt fibre enables both significant reductions in thermal conductivity and density, as well as effective shrinkage control, making the resulting compositions universal in terms of performance characteristics.

4. Discussion

The above study confirmed that varying the contents of AOBT and BFW has a substantial effect on the physical, mechanical, and thermophysical characteristics of non-autoclaved aerated concrete. First and foremost, the density data show a wide amplitude of change, indicating the material's high sensitivity to composition. Similar patterns were observed in the studies by Wu et al. [21] and Quan, et al. [22], which used other types of mineral and fibrous fillers. Their work noted a tendency for density to decrease when pore-forming components are introduced, corroborating the reliability of the results presented here. However, unlike those authors, the present study achieved a more pronounced effect, thanks to the optimised combination of AOBT and BFW, attesting to the high effectiveness of the employed formulation strategy.

Particular attention should be paid to the regression analysis, which identified the key factors influencing density changes. In particular, the dominant influence of the linear Effect of AOBT (-46.7) underscores the importance of this component as the main regulator of porosity. Studies by Feng et al. [23] and Arslan et al. [24] devoted to the influence of technogenic siliceous raw materials on the characteristics of cellular concretes likewise confirm the ability of such additives to reduce density through active gas formation. However, their models lack a pronounced positive interaction between components, which the present study addresses.

The interaction term x_1x_2 in the regression model, with a positive coefficient (+15.0), indicates a synergistic effect when AOBT and fibres are introduced together. Arun Kumar et al. [25] and Zhang et al. [26] note that similar combinations of mineral and reinforcing fillers often show competing or neutral interactions that do not improve density indices. In contrast to their results, this study shows that fibres stabilise the structure of aerated concrete even at extreme values of the gas-forming component, an effect explained by a more carefully considered approach to varying the formulation.

The quadratic terms in the model (x_1^2 and x_2^2) allow optimal ranges of component contents to be identified. The positive coefficient for x_1^2 (+12.0) indicates saturation at high AOBT concentrations, consistent with the results of [26-28], who also observed a similar trend with ash and slag additives. However, the negative coefficient for x_2^2 (-10.0) highlights a narrower effective interval for fibres, in line with the conclusions of Muthusubramanian et al. [29] and Wang et al. [30], who demonstrated agglomeration processes at elevated dosages of fibrous additives. Unlike those studies, in the present work,

the agglomeration effect is offset by interfacial interaction with AOBT.

The strength characteristics obtained at 28 days' curing show a systematic increase with increasing AOBT content, especially in combination with a moderate fibre content. Studies by Xia et al. [31] and Bhat and Khan [32] show similar behaviour when active mineral additives and reinforcing components are used in cellular concretes. However, the distinctive feature of this study is a clearly expressed strength maximum at the combination of 30% AOBT and 2% BFW, confirming the presence of a synergistic effect that was only minimally evident in the cited works.

The evaluation of non-linear effects in the strength regression model is of particular interest. The negative value of the quadratic term for x_2 (-0.27) confirms the hypothesis of reduced reinforcement efficiency at excessive fibre concentrations. This agrees with the results of Iucolano et al. [33] and Mészárosóvá et al. [34], who reported deterioration in strength indices due to fibre agglomeration and loss of uniform dispersion. Nevertheless, in the present study, the negative effects were minimised through rational proportioning, as evidenced by the comparatively high strength even in extreme mixes.

The thermal-conductivity model revealed that AOBT plays a leading role in reducing the heat-transfer coefficient by forming a closed porous structure. The results are comparable to those of Zhang et al. [35] and Xusheng et al. [36], who reported a similar effect when finely dispersed siliceous additives were used. However, unlike those works, a more significant reduction (to 0.14 W/m·°C) was achieved here, indicating a greater structural change in the material due to the introduction of BFW.

The positive interaction between components in the thermal-conductivity model ($x_1x_2 = +0.008$) indicates a stabilising role of fibres under conditions of extreme porosity. This Effect is due to the presence of basalt fibres, which promote a more stable cellular structure with predominantly closed pores and an even distribution. As a result, the likelihood of thermal bridges – typical of unstructured or unreinforced porous systems – decreases. An additional stabilising factor is the fibres' ability to prevent local coalescence of pores and channels, which is especially important at high AOBT contents that promote intensive gas formation. By contrast, [28, 37, 38] report neutral or even negative effects of reinforcing components on thermal conductivity, attributed to the formation of thermal bridges when fibres are unevenly distributed or overly concentrated. The present study contradicts that view and demonstrates that thermal conductivity can be mitigated through optimal interfacial interaction and controlled dispersion of the reinforcing component. This is confirmed both by the regression analysis and by visualization of the experimental data,

which indicate a decrease in the heat-transfer coefficient to minimum values with the combined introduction of 30% AOBT and 2% BFW.

As for drying shrinkage, the regression model shows a significant reduction in this indicator with increasing AOBT and BFW contents. The results correlate well with those of Chen et al. [39] and Melichar et al. [40], who reported a similar effect when ash and fibrous components were used. However, in their studies, the minimum shrinkage was achieved only by introducing costly synthetic fibres, whereas in the present study, this effect was achieved using technogenic raw materials, thereby increasing the practical significance of the data obtained.

Also noteworthy is the weakly expressed negative interaction between the factors ($x_1x_2 = -0.05$), indicating a synergistic effect in preventing shrinkage deformations. This manifests as an additional reduction in volumetric changes when both components, AOBT and BFW, are increased simultaneously, which is particularly important under long-term operation in variable climatic regimes. The stabilising influence is explained not only by physically constraining deformation through a reinforcing framework, but also by chemical and mineralogical processes arising from the interaction between the siliceous filler and the binder's hydration products. Eren Sarıcı and Kızılkay [41], and Seddighi et al. [42] questioned the possibility of such interaction between mineral and reinforcing components, assuming their effects to be additive and non-synergistic. However, analysis of the regression model parameters and their statistical significance indicates that the observed deviation from linearity is due precisely to the cooperative action of the components. Unlike earlier publications, the present study demonstrates a more complex pattern of interactions and highlights the need for an integrated approach to mix design that accounts for the material's physical, mechanical, and shrinkage properties.

The study by Kasymov et al. [43] examined the influence of basalt fibres on the physical and mechanical properties of concrete mixes of varying densities, using Portland cement PC400 D0 and different aggregates. The authors established that an optimal basalt-fibre dosage of up to 3% significantly improves concrete structure, increasing its strength and crack resistance, with flexural strength rising by up to 11.3% compared with the control. Exceeding the optimal content of 5% leads to fibre agglomeration and a deficit of cement paste to bind the aggregates, thereby reducing strength characteristics. The study also found that increasing basalt-fibre content reduces concrete shrinkage by forming an internal reinforcing structure that impedes particle movement. These results align with the present aerated-concrete study,

which likewise found that an optimal basalt-fibre content (2%) provides maximum strength and minimum shrinkage, while exceeding this level degrades properties due to fibre agglomeration.

In summary, the combined analysis of results indicates the high effectiveness of using AOBT and BFW together in non-autoclaved aerated concrete. Clear relationships were identified between the varied parameters and the material's main performance characteristics, including density, strength, thermal conductivity, and shrinkage. The regression models constructed confirmed the presence of linear, quadratic, and interaction effects, enabling the rational design of mixes for specified properties. The data presented confirm the promise of these components in terms of performance and economic and environmental efficiency.

5. Conclusions

The study on optimising NAAC using technogenic wastes, specifically AOBT and BFW, provides key insights into the materials' physical and mechanical properties. The greatest density reduction, down to 612 kg/m^3 , was achieved with a mix containing 30% AOBT, largely due to increased gas production and reduced solid content. The inclusion of 2% BFW further stabilised the pore structure, preventing excessive expansion during gas release, and this combination was optimal in terms of density, compressive strength, thermal conductivity, and shrinkage. The compressive strength ranged from 2.6 to 3.8 MPa, with the highest strength observed in the 30% AOBT + 2% BFW mixture, which benefited from both mineralisation and fibre reinforcement.

Thermal conductivity was significantly reduced to a range of $0.14\text{-}0.23 \text{ W/m}\cdot^\circ\text{C}$ in the optimal mix, owing to high closed porosity. The higher fibre content led to slight interference with insulation efficiency due to fibre aggregation, which affected the overall structure. The shrinkage, another crucial property, was minimal ($0.8\text{-}2.8 \text{ mm/m}$), particularly when both AOBT and BFW were used at high concentrations, indicating stabilisation of the material's volume. This synergy of low density, high compressive strength, minimal shrinkage, and low thermal conductivity demonstrated that a 30% AOBT and 2% BFW mix is the ideal composition for producing an environmentally friendly, structurally sound aerated concrete suitable for energy-efficient low-rise buildings.

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