

UDC 691.327.332
DOI: 10.56318/as/1.2025.46

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**Development of the composition and properties
of a wall block made of non-autoclaved aerated concrete based
on secondary raw materials of the Kyrgyz Republic**

Abstract. The aim of this study was to develop the composition of non-autoclaved aerated concrete using local secondary and technogenic materials to reduce production costs while ensuring compliance with strength standards. The methodology involved laboratory tests conducted at the Kyrgyz State University of Construction, Transport and Architecture named after N. Isanov, using Portland cement, quicklime, gypsum, aluminium powder and various mineral aggregates: substandard clay sand, feldspathic sand, and antimony ore beneficiation tailings (AOBT). The study varied component ratios to determine their effect on average density and compressive strength. Results showed that a minimum density of 575-580 kg/m³ was achieved with 60-70% AOBT and 30-40% feldspathic sand, owing to the increased porosity

Suggested Citation:

Matyeva, A., Melibaev, S., Sardarbekova, E., Mukanbet kyzy, E., & Asanalieva, Zh. (2025). Development of the composition and properties of a wall block made of non-autoclaved aerated concrete based on secondary raw materials of the Kyrgyz Republic. *Architectural Studies*, 11(1), 46-58. doi: 10.56318/as/1.2025.46.

Journal homepage: <https://arch-studies.com.ua/en>

Architectural Studies, 11(1), 46-58

Received: 30.07.2024 Revised: 30.12.2024 Accepted: 25.02.2025

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of the active dispersed phase. Increasing the proportion of feldspathic sand raised the density to 800 kg/m³. The use of clay sand in the range of 30-35% reduced the density to 625-650 kg/m³ due to the activation of gas formation and the development of a well-formed porous structure. The maximum strength of 2.23 MPa was achieved with 100% AOBT, owing to the high content of reactive silica and the synthesis of calcium hydrosilicates. Increasing the share of feldspathic or clay sand reduced strength to 1.61-1.66 MPa. The addition of up to 1% NaOH promoted gas generation and activation of aluminosilicate components, improving pore distribution and increasing strength while lowering density. Macroscopic structural analysis confirmed that using fine sand fractions (≤ 0.315 mm) ensures a uniform porous structure, improving both strength and thermal insulation properties of the material, whereas coarse fractions caused structural defects and a decline in performance. The practical value of this work lies in the potential application of the developed compositions in low-rise and rural construction, in the production of lightweight wall blocks by small and medium-sized enterprises, and in the expanded use of local mineral waste in the construction industry while simultaneously reducing environmental impact

Keywords: porous structure; mineral additives; pore distribution; structural strength; alkaline activation; thermal insulation properties

INTRODUCTION

The rapid development of the construction sector in the Kyrgyz Republic is accompanied by a growing demand for affordable and energy-efficient wall materials that meet modern requirements for thermal insulation, strength, and environmental safety. Particular attention is given to the production of cellular concretes, which are characterised by low density and high thermal insulation performance. Among these, non-autoclaved aerated concrete occupies a prominent position, as its production does not require expensive equipment or complex technological processes. However, a key issue remains the high cost of raw materials, driven by limited local resources and the need to import some components – a significant concern in the Kyrgyz Republic, where the construction industry is highly sensitive to price fluctuations and transportation costs.

One of the pressing challenges in developing effective wall materials is the optimisation of the structure and porosity of non-autoclaved aerated concrete while maintaining standardised strength (Shumakov *et al.*, 2024). Excessive gas formation can impair material structure, while insufficient gas generation reduces thermal insulation performance. A. Maltshik (2024) notes that in the production of non-autoclaved aerated concrete, one of the most critical issues is the selection of an effective gas-generating composition that can ensure uniform pore distribution without large defects. His studies involved various types and modifications of aluminium powder, but the author concluded that even slight deviations in the gas-forming composition result in reduced structural integrity and strength, underscoring the need for additional methods to enhance gas formation.

Equally significant is the impact of mineral aggregates on the formation of the material's porous structure. Research by Z. Mamatov *et al.* (2024) showed that the use of technogenic sands with high silica content increases strength due to the synthesis of calcium hydrosilicates. However, the study also noted that coarse aggregate fractions lead to uneven pore formation and reduced strength, necessitating further processing and grading of the raw materials. A key feature of using secondary materials is

their influence on chemical processes within the aerated concrete mixture. According to E. Boronbaev (2020), the presence of reactive minerals in technogenic raw materials promotes accelerated gas generation and the synthesis of calcium hydrosilicates. However, in some cases, excessive fine particles disrupt the material structure and reduce strength, emphasising the importance of careful dosing and mixing regimes when using such components.

The economic viability of using secondary resources in aerated concrete production also warrants separate attention. A study by J. Zhang *et al.* (2022) demonstrated that the use of industrial waste significantly reduces the cost of finished products. However, the authors emphasised that failure to account for the specific chemical composition and physico-mechanical properties of secondary materials may compromise product quality, limiting the broader application of such technologies. A particularly important aspect of research is the control of density and strength of non-autoclaved aerated concrete through varying component ratios. L. Mészárošová *et al.* (2024) found that changes in the percentage of different sands and technogenic raw materials directly affect product density and strength. While a higher proportion of active components enhances strength, it simultaneously increases density, thus diminishing the material's thermal insulation capacity. The use of chemical additives to intensify gas formation and activate mineral components has been studied by E. Michelini *et al.* (2023). They established that the introduction of alkaline activators such as NaOH increases gas output and improves pore distribution. However, the authors also noted the risk of microcracks forming when alkaline content is excessive, necessitating strict dosage control.

The formation of a uniform porous structure in aerated concrete remains one of the most complex tasks. K. Zhang *et al.* (2023) highlighted the influence of sand grain size on the material's macroscopic structure. Their study showed that fine-grained sand contributes to a uniform porous structure and enhances product strength, whereas coarse grains lead to structural defects and reduced performance





characteristics. Finally, the issue of environmental safety and the rational use of waste in construction materials is addressed by H. Song *et al.* (2023). Their work emphasised the importance of developing technologies for converting industrial waste into useful products to reduce anthropogenic environmental impact. The authors concluded that the use of such materials in aerated concrete requires careful refinement of production regimes to ensure consistent product quality.

Thus, the analysis of existing studies confirms the high relevance of developing non-autoclaved aerated concrete based on local secondary and technogenic materials in the Kyrgyz Republic. The aim of the present study was to justify the composition and examine the properties of non-autoclaved aerated concrete using local secondary raw materials to reduce costs while ensuring the standardised strength of wall blocks.

MATERIALS AND METHODS

The study was conducted in 2023 at the laboratory of the Department of Building Materials and Products Technology, Kyrgyz State University of Construction, Transport and Architecture named after N. Isanov, located in Bishkek. The laboratory was selected for its specialisation and advanced experimental facilities, enabling complete reproduction of the technological cycle for producing aerated concrete. The main components of the composite binder included Portland cement grade M400 D20 in accordance with GOST 31108-2020 (2020), quicklime of the second grade in lump form with a combined content of active components (MgO and CaO) of 82%, and a fraction of unreacted particles not exceeding 1.2%, as well as construction gypsum grade G-5 in accordance with GOST 125-79 (1980). Gas formation in the mixtures was achieved using aluminium powder grade PAP-2 produced in China, compliant with GOST 5494-95 (1996).

The mineral fillers included substandard fine-grained clay sand from the Kyzyl-Kyshtak and Ak-Zhar deposits in the Kara-Suu district of Osh region, feldspar sand, and antimony ore beneficiation tailings (AOBT) from the Kadamjai Antimony Plant in Batken region. AOBT was formed during the extraction of antimony from ores under thermal treatment at 1200°C and had the following chemical composition (in %): CaO – 12.67; R₂O – 0.67; Al₂O₃ – 6.92; Fe₂O₃ – 0.73; SiO₂ – 70.93; MgO – 0.03; SO₃ – 0.82; loss on ignition – 7. The mineral composition was dominated by quartz and calcite, with minor amounts of clay minerals. The grindability coefficient of AOBT was 1.2, indicating high friability and good grindability.

The substandard clay sand contained the following components (in %): CaO – 0.86; SiO₂ – 73.74; R₂O – 4.27; Al₂O₃ – 12.52; Fe₂O₃ – 0.93; SO₃ – 0.4; MgO – 2.85; loss on ignition – 4.41. Its mineralogical composition included 31.67% Al₂O₃ • 2SiO₂ • 2H₂O, 59.01% free silica, 5.98% magnesite, 1.03% calcite, and 0.68% gypsum. The sandstone was dry-ground for 20-25 minutes to a fraction below 0.16 mm, achieving a specific surface area of 2,200-2,250

cm²/g. Feldspar sand had the following oxide composition (in %): Al₂O₃ – 14.21; SiO₂ – 68.72; MgO – 2.68; CaO – 3.25; SO₃ – 2.61; Fe₂O₃ – 3.24; TiO₂ – 6.63. To activate the clay component and intensify gas formation, up to 1% sodium hydroxide (NaOH) of Chinese origin was added to the mixtures. The development of aerated concrete mixtures involved varying the mass ratios of dispersed fillers and feldspar sand from 0/100 to 100/0. The binder-to-filler ratio was maintained between 0.5 and 1. Mixing was carried out until a homogeneous mass was achieved. The workability was evaluated using the Suttard Viscometer (USA), which determines the structural viscosity of aerated concrete mixtures. The average value was 29-30 cm.

Test samples were moulded in metal forms measuring 15×15×15 cm. Curing was performed under natural conditions at a temperature of 20-25°C and relative humidity of 60-70% for 28 days. The average density was determined in accordance with GOST 31359-2024 (2024), and compressive strength was tested in accordance with GOST 10180-2012 (2012). Compressive strength was measured using a hydraulic press machine Controls MCC8 50-C10A05 (Italy) with a maximum load of 3,000 kN and a digital force registration system with an accuracy of 0.01 MPa. The pore structure of the aerated concrete was analysed using a Levenhuk 700M optical microscope (USA), providing up to 40× magnification, allowing visualisation of pore geometry, distribution, and the nature of inter-pore walls. Studies were conducted on horizontal polished sections of samples after 28 days of curing. Microphotographs were taken using the microscope's digital camera for further morphometric analysis. Statistical analysis of the experimental data was conducted using Student's t-test at a significance level of $p < 0.05$. All measurements were performed in triplicate to ensure high data reliability. Calculations were carried out using Microsoft Excel 2019 (USA) and the Statistica 10.0 (USA) statistical software package, enabling reliable analysis of variance, normality testing, and construction of confidence intervals.

RESULTS

The study of the influence of various ratios of technogenic and natural mineral fillers on the average density of non-autoclaved aerated concrete revealed a clear pattern of variation in this parameter. The lowest density values were recorded with 60-70% AOBT and 30-40% feldspar sand. In these compositions, the average density was 575-580 kg/m³, which represented the best performance among all tested variants (Table 1). As the proportion of feldspar sand increased, the density of aerated concrete rose, reaching 800 kg/m³ at 100% feldspar content. The use of off-spec sand with a clay component also influenced the density. When its content was within 30-35%, the density reached minimum values of 625-650 kg/m³. This dependence is attributed to the material's overall mass reduction due to high porosity, ensured by the active clay fraction. Therefore, the optimal filler ratio allows regulation of aerated concrete density across a wide range.

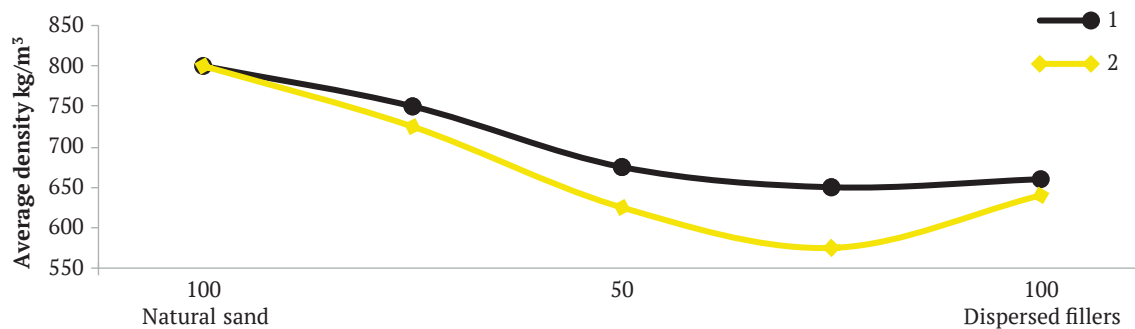
**Table 1.** Influence of filler ratios on the average density of non-autoclaved aerated concrete

Mix No.	AOBT/Feldspar sand (%)	Off-spec sand/Feldspar sand (%)	ρ_{avg} , kg/m ³
1	0/100	-	800
2	15/85	-	760
3	30/70	-	730
4	40/60	-	670
5	50/50	-	630
6	60/40	-	580
7	70/30	-	575
8	85/15	-	610
9	100/0	-	640
10	-	0/100	800
11	-	15/85	761
12	-	30/70	740
13	-	40/60	720
14	-	50/50	670
15	-	60/40	650
16	-	70/30	625
17	-	85/15	640
18	-	100/0	655

Source: compiled by the authors

The obtained experimental results established a clear relationship between the content of the technogenic component AOBT, natural feldspar sand, and off-spec clayey sand, and the average density of non-autoclaved aerated concrete. Minimum density values were observed in compositions

containing 60-70% AOBT and a reduced proportion of feldspar sand (30-40%) (Fig. 1). The corresponding density reached 575-580 kg/m³, attributed to the high reactivity of the dispersed phase, which facilitated intensive gas formation and the development of a well-formed porous structure.

**Figure 1.** Dependence of average aerated concrete density on filler composition

Notes: 1 – off-spec sand and feldspar sand; 2 – AOBT and feldspar sand

Source: compiled by the authors

The high effectiveness of AOBT is linked to its mineral composition, which is dominated by quartz and calcite. This facilitated the formation of loosely bound frameworks among the porous formations, reducing the overall material mass without significant strength loss. Increasing the feldspar sand content led to a rise in average material density up to 800 kg/m³. This process is explained by the low dispersity of feldspar sand, reduced gas formation, and, consequently, decreased volume of closed pores.

A similar trend was observed in mixtures with off-spec clayey sand, where minimum density values of 625-650 kg/m³ were achieved with 30-35% active clay content. The high aluminosilicate content in the clayey sand promoted additional gas formation activation and enhanced porosity due to interactions with sodium hydroxide

and binder components. This enabled the formation of a looser structure dominated by small, spherical pores, reducing the final product's mass.

It is worth noting that further increases in feldspar sand content or its complete substitution resulted in higher material density. This is due to the insufficient activity and weak propensity of feldspar sand to participate in pore-forming reactions, thereby limiting the development of a microporous structure. A higher proportion of coarse fractions led to a loss of connectivity among porous elements and increased the density of inter-pore walls.

Thus, the optimal reduction in average density was achieved within a narrow range of compositions combining active technogenic additives with a controlled amount of feldspar sand. These patterns highlight the importance



of selecting the granulometric and mineralogical composition of fillers to obtain lightweight porous materials with adjustable density.

Experimental data demonstrated a clear dependence of the compressive strength of non-autoclaved aerated concrete on the percentage content of different types of fillers (Fig. 2). The highest strength values – up to 2.23 MPa – were recorded when using 100% AOBT due to the high activity of its siliceous component. Strength indicators consistently

increased with the proportion of AOBT, reaching a peak within the 70-100% range of the total filler content. Conversely, the lowest compressive strength values (1.61-1.66 MPa) were observed in compositions where the main component was either feldspathic sand or substandard clay sand with insufficient content of active siliceous material. These results confirm that a high proportion of active technogenic material contributes to the formation of a robust framework and enhances the mechanical properties of the aerated concrete.

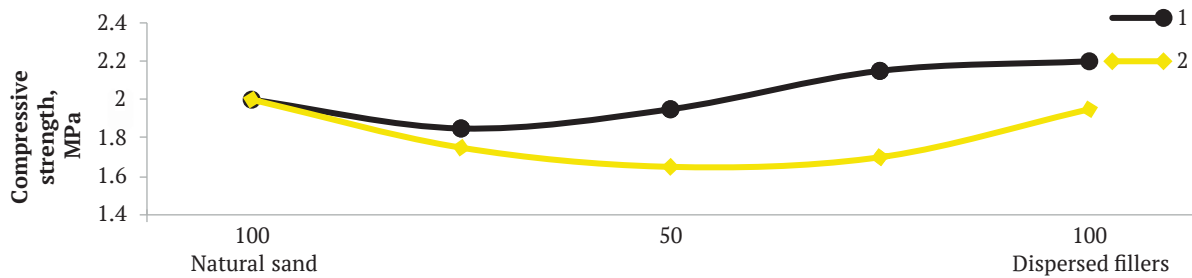


Figure 2. Dependence of compressive strength of aerated concrete on filler composition

Notes: 1 – AOBT and feldspathic sand; 2 – substandard sand and feldspathic sand

Source: compiled by the authors

The experimental results revealed a distinct correlation between the compressive strength of non-autoclaved aerated concrete and both the qualitative and quantitative composition of the mineral fillers. A significant increase in strength was observed in mixtures where the mass fraction of CRIW as an active component ranged from 60 to 100%. Peak strength values reached 2.23 MPa when feldspathic sand was completely replaced by AOBT. This is attributed to the high free silica content and the presence of active phases in AOBT, which actively participated in cement hydration processes and reacted with calcium hydroxide hydrate to form additional quantities of calcium hydrosilicates, thus strengthening the inter-pore walls and improving the structural characteristics of the concrete.

An additional factor enhancing strength was the mineralogical nature of AOBT: the predominance of quartz and calcite facilitated the synthesis of robust silicate and carbonate phases, forming a dense crystalline structure within the aerated concrete. The formation of the primary framework through AOBT stabilised the structure formation process, prevented shrinkage cracking, and ensured uniform pore distribution, thereby reducing the risk of local deformations and increasing the mechanical stability of the material. In contrast, increasing the content of feldspathic sand had the opposite effect – reducing the concrete's strength to minimum values in the range of 1.61-1.66 MPa. This is due to its low chemical reactivity and minimal participation in the formation of new durable phases. Feldspathic sand hardly integrated into the hydrosilicate structure, acting instead as an inert mass, disrupting cement matrix cohesion and worsening strength characteristics. The large and dense feldspar particles impeded the formation of a robust fine-pored structure, leading to local stress redistribution and microcrack formation.

Substandard clay sand exhibited a similar trend of strength reduction, especially at high contents and insufficient alkaline activation. High clay mineral content without NaOH treatment led to the formation of loose, weakly bonded aggregates that did not contribute to the formation of a durable crystalline framework. However, introducing up to 1% sodium hydroxide into the mix activated the clay component. This facilitated additional calcium hydrosilicate synthesis and partially offset the reduction in strength characteristics, which was clearly evident in intermediate compositions with an active component content of at least 60%.

An interesting feature was the stabilisation of strength in mixtures that combined the active siliceous additive with a moderate amount of feldspathic sand. Here, strength reached 2.15-2.2 MPa due to the combined influence of mineralogical composition and a properly managed gas generation process, which led to the formation of a stable cellular structure. These systems exhibited a synergistic effect: active components promoted the formation of a strong crystalline phase, while the inert portion ensured volumetric stability. In conclusion, the highest compressive strength values of non-autoclaved aerated concrete were achieved through the combined action of active AOBT phases, optimal material macrostructure, and the synthesis of hydrate formations that effectively reinforced the inter-pore walls. This highlights the importance of carefully selecting filler types and their ratios when designing strong and durable cellular construction materials.

Macrostructural analysis of horizontal cross-sections of aerated concrete samples revealed a direct dependence of pore structure formation on the granulometric composition of the sands used (Fig. 3). When sand fractions between 0.63 and 0.315 mm were introduced into the mix, large elongated and interconnected pores of 0.5 to 3 mm



in size were observed. These pores predominantly had slit-like or irregular shapes, which negatively affected the density and homogeneity of the inter-pore walls. Such

structures reduced the overall strength of the aerated concrete by up to 10% compared with samples made with finer sand fractions.

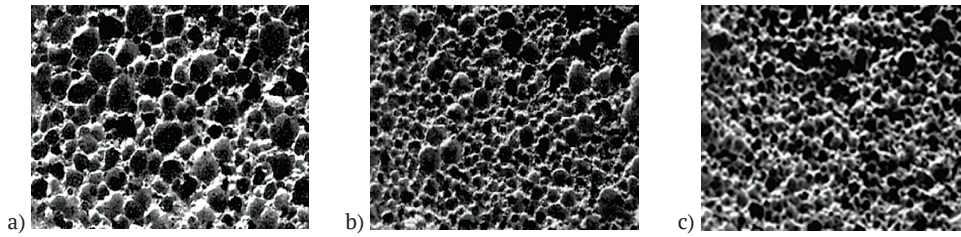


Figure 3. Macrostructure of horizontal cross-sections of aerated concrete samples using different sand fractions ($\times 10$)

Notes: a) coarse fraction; b) medium fraction; c) fine fraction

Source: compiled by the authors

At the same time, the use of fine sand fractions – 0.315 mm and smaller – ensured the formation of a uniform fine-pored structure, which significantly influenced the morphological and performance characteristics of the resulting material. The pore sizes in these specimens ranged from 0.3 to 1.2 mm, with most of the pores being oval or nearly spherical in shape, indicating the stability of the foaming process and the uniform distribution of the gaseous phase throughout the material's volume. Such a porous structure contributed to the reduction in the thickness of the inter-pore walls, thereby increasing the density and strength of the framework. This, in turn, led to the formation of a denser and more robust system capable of efficiently withstanding mechanical loads. Additionally, the presence of small, evenly distributed pores reduced the likelihood of defect formation and localised stresses, which positively affected the material's durability and resistance to external influences. Thus, the use of fine sand can be regarded as one of the effective methods of controlling the structure and mechanical properties of the material.

The results of macrostructural analysis confirmed the critical role of the granulometric composition of sand aggregates in the structuring processes of non-autoclaved aerated concrete. The size and shape of the sand fractions directly affected not only the overall density and strength of the material, but also the nature of pore distribution, and consequently, the durability and reliability of aerated concrete products in service. The use of coarse sand fractions ranging from 0.63 to 0.315 mm in the aerated concrete mix resulted predominantly in the formation of a macroporous structure. In such specimens, large, deformed and interconnected pores ranging from 0.5 to 3 mm were observed. The geometry of the pores was mainly elongated, with a pronounced slit-like or irregular shape. This had a negative effect on structural homogeneity – inter-pore walls became loose and less robust, which led to a considerable reduction in overall material strength, by up to 10%.

The reasons for this effect are associated with the insufficient wettability of large sand grains by the cement slurry and their limited involvement in the structure-forming processes. Coarse fractions hindered the

uniform distribution of the gas-generating medium, creating zones of local stress redistribution. This promoted the formation of microcracks and disrupted structural continuity, thereby reducing the mechanical stability of the aerated concrete. The opposite effect was observed when fine-grained sand with a particle size of 0.315 mm and smaller was used in the aerated concrete mix. In this case, the material structure was characterised by the uniform distribution of small pores ranging from 0.3 to 1.2 mm. Most of the pores were rounded or oval, close to spherical, which helped reduce stress concentrations in the inter-pore walls. This structure not only improved the strength characteristics of aerated concrete but also enhanced its thermal insulation properties due to the increased proportion of closed air voids.

The high dispersion degree of fine sand fractions ensured intensive interaction with binding components and active participation in gas generation processes. This made it possible to create a well-developed fine-pored structure with increased specific surface area, capable of effectively resisting mechanical stress. Moreover, the reduction in pore size contributed to an increase in their number per unit volume, thereby lowering the overall density of the material without loss of strength. An important factor in improving the strength and uniformity of the aerated concrete structure was also the ability of fine sand particles to form strong and dense inter-pore partitions. This hindered the development of microcracks and ensured the material's resistance to long-term service loads.

Thus, the use of fine-grained sand in aerated concrete mixtures is a necessary condition for producing high-quality non-autoclaved aerated concrete with a uniform cellular structure, optimal density, and enhanced strength. The research results emphasise the need for strict control of the granulometric composition of aggregates at the stage of raw material selection and mix preparation. The introduction of sodium hydroxide (NaOH) into aerated concrete mixtures in quantities up to 1% of the total component mass had a significant effect on the intensification of gas formation and the activation of the clay component of the mineral aggregates. The alkaline environment created by





NaOH contributed to the increased activity of aluminosilicate minerals contained in substandard clay sand and ensured fuller expression of their reactive potential. Simultaneously, the rate of gas formation from aluminium powder increased due to the accelerated chemical reaction with hydrated lime. This led to the formation of a more uniform and developed porous structure with an increased number of fine closed pores. As a result, the strength characteristics of the aerated concrete improved, and its density decreased due to more efficient synthesis of calcium hydrosilicates and the formation of a dense macrostructural framework.

Primarily, NaOH, by creating a highly alkaline environment in the system, activates aluminosilicate minerals contained in substandard clay sand and high-activity mineral waste (HMW). Under the influence of the alkali, the crystal lattice of clay minerals such as montmorillonite and kaolinite is destroyed, releasing active silicon and aluminium ions into solution. These ions, reacting with the hydrated phase of the cementitious binder, initiate the formation of new strong crystalline compounds, primarily calcium hydrosilicates and calcium hydroaluminosulphates. As a result, the macrostructural framework of the material is significantly strengthened, the strength of inter-pore partitions increases, and the overall mechanical strength of the aerated concrete is improved.

Equally important is the role of NaOH in intensifying gas formation. Aluminium powder, used as the gas-generating agent, reacts much faster and more intensively in the alkaline environment with water and hydrated lime. This ensures uniform pore distribution throughout the mass, prevents the formation of large voids and local defects. As a result, an optimal fine-pored structure with predominantly round closed pores is formed, providing not only mechanical strength but also excellent thermal insulation properties. Alkaline activation also promotes the involvement of previously inert mineral fractions, particularly components of feldspathic sand, in the structure-forming process. Under the influence of NaOH, partial degradation of the feldspar surface occurs, facilitating better bonding with the binder and strengthening the overall structure of the material. Thus, NaOH offsets the negative effects of low-reactivity components in the composition, expands the raw material base, and increases the efficiency of local mineral waste utilisation.

Experimental studies established that the introduction of NaOH in quantities up to 1% of the dry component mass ensures the optimal balance between density and strength of the aerated concrete. At this concentration, maximum synthesis of calcium hydrosilicate phases and uniform pore distribution are achieved. Exceeding the optimal dosage leads to excessive gas formation rates, which can result in macro-defects and, consequently, a decrease in the strength of the final material. Hence, NaOH performs a dual role – as both activator and modifier. On the one hand, it significantly enhances the utilisation of siliceous and clay components, thereby promoting the recycling of local technogenic wastes. On the other hand, it stimulates the

formation of a robust macrostructural framework through targeted synthesis of hydrated phases. These combined effects allow the production of non-autoclaved aerated concrete with high physical and mechanical performance and stable structure at minimal density. The findings demonstrate that the use of NaOH not only improves the efficiency of structure formation processes but also significantly expands the applicability of local secondary resources, reducing costs and environmental impact.

DISCUSSION

The findings of this study demonstrated a pronounced effect of the ratio between technogenic and natural mineral aggregates on the density and strength of non-autoclaved aerated concrete. The lowest density values were recorded when 60-70% HMW was introduced into the mixture, confirming their effectiveness in forming a lightweight porous structure. Similar patterns were obtained in the study by A. Paul *et al.* (2025), which showed the effect of highly dispersed technogenic waste on reducing the density of cellular concretes through enhanced gas formation. The observed correlation between increased feldspathic sand content and increased material density aligns with the findings of Y. Peng *et al.* (2021), who demonstrated the limited activity of feldspars in chemical interaction with binders. However, their study did not take structural effects into account, whereas the present work has shown that feldspar reduces the intensity of gas formation, increasing mass and density.

The use of substandard clay sand in the range of 30-35% led to a reduction in aerated concrete density to 625-650 kg/m³, which is explained by the high pore-forming capacity of active aluminosilicate phases. Similar conclusions were drawn by G. Murali & M. Azab (2023), who emphasised the role of the clay fraction in enhancing system porosity. At the same time, the study by F. Seddighi *et al.* (2021) did not find a significant impact of clay sand on the density of cellular concretes, attributing this to the low activity of the components. Unlike their work, the present study demonstrated that activation of the clay component is achieved through the alkaline environment, which enables the full reactive potential of the minerals to be realised.

Maximum compressive strength (2.23 MPa) was recorded when 100% AOBT was used, which is attributed to the high content of free silica and calcite. These results are consistent with the findings of R. Wu *et al.* (2021), who demonstrated the strengthening of aerated concrete structure through the synthesis of calcium hydrosilicate phases with an increase in active siliceous components. A reduction in strength to 1.61-1.66 MPa with an increasing proportion of feldspar sand supports the conclusions of J. Xia *et al.* (2021), who pointed to the inertness of feldspars and their weak participation in hydration reactions. However, the present study provides a more detailed insight into the mechanism of structural disintegration due to the formation of weak inter-pore partitions.

Particular attention is drawn to the stabilisation of strength at the level of 2.15-2.2 MPa when combining the



active siliceous component with a moderate amount of feldspar sand. A similar synergistic effect was reported by S. Mollaei *et al.* (2022), who observed structural optimisation through the combination of active and inert fillers. A contrasting viewpoint is presented by O. Oladiran & D. Simeon (2023), who claimed that the addition of inert fractions always leads to a decrease in strength. However, their study did not account for the effect of particle size distribution on stress redistribution and the formation of a stable framework, which is considered in the present research. Macrostructural analysis confirmed the key role of sand particle size in the processes of structural formation. The formation of a macroporous structure when using coarse fractions (0.63–0.315 mm) led to a 10% decrease in strength.

Conversely, the use of fine fractions up to 0.315 mm ensured the formation of a uniform microporous structure with pore sizes ranging from 0.3 to 1.2 mm. The effectiveness of this approach is supported by the study of C. Liu *et al.* (2021), who demonstrated significant improvements in the mechanical properties of cellular concrete when using fine fillers. Additionally, it was found that the application of fine fractions not only ensures uniform distribution of the gas phase but also increases the density of inter-pore partitions due to the tighter packing of small particles against the binder matrix. This contributes to the formation of a strong and homogeneous framework, resistant to external loads and minimising the risk of microcracks. As a result, aerated concrete acquires not only high strength but also improved thermal insulation properties due to the increased proportion of closed spherical pores (Basok *et al.*, 2023). Furthermore, the uniform microporous structure reduces water absorption and enhances the durability of the material under humid operating conditions.

An opposite result was reported by B. Aramburu *et al.* (2024), where fine sand fractions led to reduced strength due to increased water demand of the mixture. The additional water required to maintain the necessary workability of the mix with fine fractions resulted in excessive porosity and structural weakening. However, the present study shows that the active interaction of fine particles with the binder reinforces the inter-pore partitions and enhances strength. Fine fractions contribute to more uniform component distribution and close adhesion to the binder matrix, reducing the likelihood of weak zones and increasing the number of closed pores (Montayev *et al.*, 2016). This not only improves strength characteristics but also enhances the thermal insulation properties of aerated concrete through the formation of a uniform microporous structure.

Special emphasis was placed on the effect of sodium hydroxide on the structural formation of aerated concrete. The introduction of NaOH up to 1% of the component mass activated aluminosilicate minerals, enhancing the synthesis of calcium hydrosilicate phases and structural reinforcement (Astakhova & Astakhov, 2024). The alkaline environment facilitated the breakdown of the crystalline lattice of clay minerals such as montmorillonite

and kaolinite, allowing the release of reactive silicon and aluminium ions into the solution and their further participation in hydration reactions. This had a positive impact on the formation of a dense macrostructural framework, improving the strength characteristics of the material. Similar results were presented by W. Jin (2022), where alkaline activation improved the strength properties of cellular materials and contributed to a more uniform distribution of the porous structure.

However, X. Ma *et al.* (2022) highlighted the risk of excess alkali, which causes excessive gas formation and reduces strength. According to their findings, exceeding the permissible NaOH dosage leads to uneven gas phase expansion, the formation of macro-defects, and weakening of the material structure. The present study confirmed this observation, recording a reduction in strength when the optimal NaOH dosage was exceeded, underscoring the necessity of strict dosage control to achieve the required performance characteristics of the material.

It is noteworthy that additional activation of feldspar sand under the action of NaOH was identified. This effect was previously described by B. Muthusubramanian *et al.* (2023), who showed the possibility of partial destruction of feldspars and enhanced bonding with the cement matrix. The breakdown of feldspar grain surfaces and the increase in their reactivity result in a stronger bond between inert particles and the binder, which contributes to the overall improvement of the material structure and reduces the risk of weak zones in aerated concrete.

In contrast, A. Thakur & S. Kumar (2022) expressed doubts about the feasibility of using NaOH to activate low-reactivity components, citing potential economic costs and limited effectiveness of such additives in mixtures with high inert content. However, the present study demonstrates a positive outcome when the optimal dosage is observed, allowing the activation of feldspars and clay minerals without adverse effects on gas distribution uniformity and material strength.

The findings also agree with the conclusions of W. Quan *et al.* (2024), who proved that the use of alkaline activators expands the raw material base and allows for the effective utilisation of industrial waste. Furthermore, W. Quan *et al.* emphasised that this technology helps reduce reliance on traditional natural resources and enables the creation of building materials with specified performance characteristics through the incorporation of previously unsuitable components.

Meanwhile, G. Chen *et al.* (2021) noted the limited effectiveness of aluminosilicate activation under high humidity conditions. According to their results, high humidity prevents the full development of the reactivity of aluminosilicate minerals and limits the formation of durable hydrate phases, which negatively affects the material's strength properties. However, in the present study, these negative effects were mitigated by strict control of the moisture regime at all stages of the technological process and by optimising the mixture composition, including





adjusting the water-cement ratio and introducing additional modifiers. This ensured the stability of hydration and gas-forming processes, contributing to the formation of a strong and homogeneous structure of aerated concrete even under potentially high moisture conditions.

Particular attention should be paid to the establishment of the positive effect of NaOH on pore distribution uniformity and the formation of a stable cellular structure. Alkaline activation promotes the even distribution of the gas phase within the material volume, preventing the formation of local compactions and voids, which is critically important for structural stability during operation (Yakovkin *et al.*, 1998). As a result, the likelihood of defects such as through-channels or large open pores that could negatively affect strength and thermal insulation properties is reduced. Similar results were reported by M. Arslan *et al.* (2021), who demonstrated increased thermal insulation properties of aerated concrete when using alkaline activators. Moreover, M. Arslan *et al.* noted improvements in macrostructure due to the formation of uniform and predominantly spherical pores, further contributing to the material's durability and its ability to maintain performance under long-term exposure to external factors.

Conversely, T. Pi *et al.* (2021) reported a reduction in thermal insulation properties due to excessive material density when using NaOH. T. Pi *et al.* emphasised that increased density impairs the thermal insulation efficiency of aerated concrete, limiting its use as an energy-saving construction material. However, the present study demonstrates the achievement of an optimal balance between density and strength, allowing good thermal insulation properties to be maintained while ensuring the required level of mechanical strength. This is achieved through precise control of NaOH dosage, which promotes the formation of a uniform microporous structure with a predominance of closed pores that ensure low thermal conductivity and resistance to thermal deformation.

The influence of NaOH on pore redistribution and the prevention of large void formation correlates with the findings of P. Walczak (2023), who demonstrated a reduction in the likelihood of defects and microcracks under alkaline activation. This effect is explained by the fact that the presence of alkali promotes a more uniform progression of gas-forming reactions and stabilises the size of the forming pores, thereby preventing the coalescence of individual gas bubbles into large cavities (Timchenko *et al.*, 2023). This ensures structural homogeneity and contributes to the formation of dense inter-pore partitions with enhanced strength. Furthermore, alkaline activation enhances the bonding of silicon and aluminium ions within the material's structure, facilitating the synthesis of additional durable phases, which has a positive effect on the mechanical stability and durability of aerated concrete under cyclic loads and external influences.

At the same time, C.Q. Wang *et al.* (2020) criticised the use of NaOH, claiming that it increases production costs and environmental risks. They point out that the use of

alkaline additives requires additional expenditure for chemical reagents and the establishment of control systems for their dosing. It may also lead to an increased burden on wastewater treatment facilities due to the formation of alkaline effluents. However, the present study, in contrast, demonstrates that the application of NaOH in optimal dosages can reduce costs through the utilisation of waste materials and the expansion of the raw material base by incorporating low-reactivity and difficult-to-utilise mineral components. Moreover, the use of NaOH intensifies gas evolution processes and the synthesis of strong phases, allowing a reduction in binder consumption and improving overall production efficiency, thereby minimising reliance on traditionally expensive components.

The final conclusions are supported by the studies of E. Yusrianto *et al.* (2022) and E.K. Sardarbekova *et al.* (2022), who highlighted the importance of a comprehensive approach to the selection of aggregates and modifiers for producing aerated concrete with high physical and mechanical properties. Particular emphasis is placed on the necessity of considering not only the chemical and mineralogical composition of the components but also their granulometric characteristics, which enables control over gas evolution and the formation of the porous structure. Additionally, E. Yusrianto *et al.* noted the significance of optimal activator dosages, including alkaline components, to maximise the efficiency of strong phase synthesis and enhance the durability of the material. Such an integrated approach makes it possible to improve the performance characteristics of aerated concrete, including strength, density, and thermal insulation parameters, thus rendering the material competitive for use in various climatic zones and structural applications.

Thus, the study proved the effectiveness of the complex selection of mineral aggregates and the use of NaOH to regulate the properties of non-autoclaved aerated concrete. The optimum ranges of components content have been established, providing the achievement of minimum density while maintaining high strength and stability of the structure. The results emphasise the importance of further study of alkaline activation mechanisms and possibilities of technogenic waste utilisation for the creation of energy-efficient building materials.

CONCLUSIONS

The conducted experimental research made it possible to establish clear correlations between the content of various mineral fillers and the physical-mechanical properties of non-autoclaved aerated concrete. It was determined that the use of AOBT contributes to a reduction in the material's average density and an increase in strength due to the high reactivity of its silica component. The optimal composition 60-70% AOBT and 30-40% feldspathic sand ensured the formation of a uniform porous structure with a minimum density of 575-580 kg/m³ and a compressive strength of up to 2.15-2.2 MPa. Increasing the proportion of feldspathic sand led to a rise in the density of aerated concrete up to



800 kg/m³ and a reduction in strength to 1.61-1.66 MPa, which is attributed to its inertness and weak contribution to the formation of a robust macrostructural framework. The introduction of substandard clay sand in amounts of up to 30-35% resulted in a decrease in density to 625-650 kg/m³ due to the activation of gas evolution by the aluminosilicate fraction.

Maximum compressive strength values up to 2.23 MPa were achieved with a AOBT content in the range of 70-100%. This is associated with the formation of additional hydrate phases that reinforce the inter-pore partitions and increase the structural integrity of the material. Macrostructural analysis showed that the use of fine-grained sands (fraction <0.315 mm) supports the formation of a uniform cellular structure with small, closed pores, thereby improving the strength and thermal insulation properties of the aerated concrete. The addition of up to 1% NaOH effectively activates the clay components and enhances gas evolution, which further improves the material's structure and mechanical properties. Alkaline activation also broadens the possibilities for recycling local

mineral waste and increases the raw material flexibility of the technology.

In practice, it is recommended to focus on formulations with high AOBT content and fine-grained sands, as well as to employ alkaline activation to produce lightweight and strong aerated concrete with controlled density. A limitation of the study is its laboratory scale, which necessitates further full-scale testing and evaluation of performance under real construction conditions. Promising directions for future research include optimisation of curing regimes and the study of material durability in different climatic conditions.

ACKNOWLEDGEMENTS

None.

FUNDING

None.

CONFLICT OF INTEREST

None.

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Розробка складу і властивості стінового блоку з неавтоклавною газобетону на основі вторинної сировини Киргизької Республіки

Анотація. Метою дослідження було розроблення складу неавтоклавною газобетону із застосуванням місцевих вторинних і техногенних матеріалів для зниження собівартості при забезпеченні нормативної міцності. Методологія включала лабораторні випробування на базі Киргизького державного університету будівництва, транспорту і архітектури з використанням портландцементу, негашеного вапна, гіпсу, алюмінієвої пудри і різних мінеральних заповнювачів: некондиційного глинистого піску, польовошпатового піску та хвостів збагачення сурм'яних руд (ХЗСР). Дослідження проводили за варіювання співвідношень компонентів для визначення впливу на середню густину і міцність на стиск. Результати показали, що мінімальна густина 575-580 кг/м³ досягалася за вмісту 60-70 % ХЗСР і 30-40 % польовошпатового піску за рахунок збільшеної пористості активної дисперсної фази. Підвищення частки польовошпатового піску збільшувало щільність до 800 кг/м³. Використання глинистого піску в межах 30-35 % знижувало густину до 625-650 кг/м³ за рахунок активізації газоутворення і формування розвиненої пористої структури. Максимальна міцність 2,23 МПа досягалася при 100 % ХЗСР завдяки високому вмісту активного кремнезему і синтезу гідросилікатів кальцію. Збільшення частки польовошпатового або глинистого піску знижувало міцність до 1,61-1,66 МПа. Додавання до 1 % NaOH сприяло інтенсифікації газоутворення та активації алюмосилікатних компонентів, покращуючи розподіл пір і підвищуючи міцність при зниженні щільності. Макроструктурний аналіз підтвердив, що застосування піску дрібних фракцій ($\leq 0,315$ мм) забезпечує рівномірну пористу структуру, покращуючи міцність і теплоізоляційні властивості матеріалу, в той час як великі фракції викликали структурні дефекти і зниження характеристик. Практична цінність роботи полягає в можливості застосування розроблених складів у малоповерховому та сільському будівництві, при виробництві легких стінових блоків в умовах малого та середнього бізнесу, а також для розширення використання місцевих мінеральних відходів у будівельній галузі з одночасним зниженням екологічного навантаження

Ключові слова: пориста структура; мінеральні добавки; розподіл пір; структурна міцність; лужна активація; теплоізоляційні властивості