

Lightweight Porous Concrete Based on Dry Mixes

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Abstract

This article investigates lightweight porous concrete (LPC) produced from dry mechanically activated mixtures and evaluates the effect of porous aggregates on its physical and mechanical properties. Dry mixtures based on PC500 D0 Portland cement, foam glass, expanded clay, and expanded polystyrene granules were modified using KZ-TM-30 polysilicic acid sol. The nanomodifier improved particle size distribution toward finer fractions, resulting in increased early strength. Compressive and flexural strength, shrinkage, frost resistance, and thermal conductivity of LPC were determined, while microstructural analysis confirmed strong adhesion between the aggregate and cement matrix. The results demonstrate the effectiveness of nanomodified dry mixtures for producing high-performance lightweight concretes with thermal insulation and structural properties.

Keywords: Lightweight porous concrete, dry mix, nanoscale modification, microstructure, strength, slump, frost resistance, thermal conductivity coefficient.

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1. Introduction

The challenge of reducing the weight of building and structural components has always been one of the most pressing scientific and technical priorities in the field, and it remains relevant today. This objective is typically achieved through two primary approaches. The first approach is to increase the strength and modulus of elasticity of the materials used in load-bearing structures. This allows for a reduction in the cross-sectional dimensions of the structure, consequently decreasing its total volume and weight. The second approach consists of reducing the average bulk density of materials used for

enclosing structures, while simultaneously improving their resistance to thermal conductivity, sound insulation properties, and structural quality factor (i.e., specific strength). As a result, the thickness of wall and roofing elements is reduced, and in general, the total volume of the structures decreases.

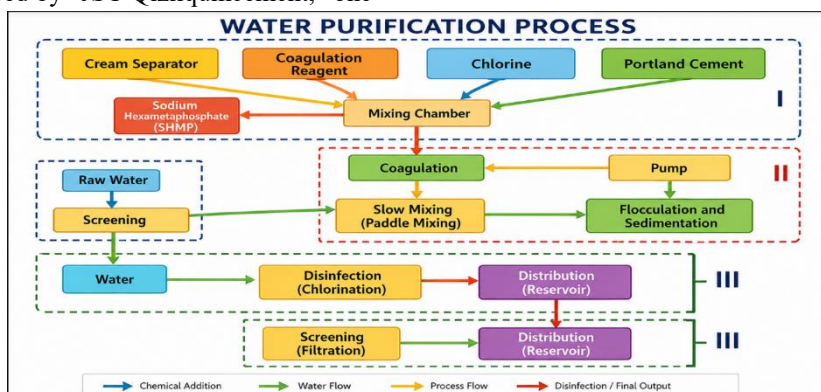
Lightweight cement-based concretes have long been widely used in the wall structures of modern multi-story and, in particular, low-rise residential buildings. According to the requirements of GOST 25820-2014, they are classified by their structural characteristics into dense, large-pored, and aerated types. Within this classification, the aerated type is considered the closest

to the concept of lightweight concrete. This is because not only the aggregate but also the matrix—the cement stone—has a porous structure, which results in a relatively uniform internal structure of the material.

From this perspective, it is considered advisable to implement a single-stage technology for producing lightweight concretes that are more effective than existing analogues. This technology is based on a dry, aerated, and activated mixture combined with porous aggregates. The advantage of this approach is that it creates broad opportunities to modify the dry mixture through physicochemical methods, particularly by introducing nanoscale additives. This, in turn, allows for the targeted regulation and control of the technological parameters and physical-mechanical properties of the lightweight concrete mix.

During the preparation of the dry mix for lightweight porous concretes, Portland cement grade PC500 D0 (CEM I 42.5), produced by "JSC Qizilqumcement," one

of Uzbekistan's largest cement manufacturers, was used. As a filler, granulated foam glass based on cullet with a bulk density in the range of 130–275 kg/m³, manufactured by Navoi Steklo Lyuks LLC, was utilized. Additionally, in accordance with Uzbek standards (equivalent to O'zDST 32496–2013), expanded clay aggregate grades D300 and D400, and expanded polystyrene granules with a bulk density of 10 kg/m³ were used. To create pores in the cement matrix, a foaming agent available on the Uzbek market (such as the PB 2000 type) intended for foam concrete production was employed. As a nanomodifier, a polysilicic acid sol of the KZ-TM-30 type, produced in Uzbekistan, was used for the nanomodification of dry mixes for lightweight porous concretes. Previous studies have confirmed the high efficiency of silica-based additives, which are also convenient for use in the technology of preparing dry mixes.



The production process for lightweight porous concrete based on dry mechanically activated mixtures (Figure 1) can be divided into three interconnected stages that yield three different types of finished products.

These are as follows:

- a dry mix for the production of foam concrete;
- a dry mix with a lightweight filler for the preparation of lightweight porous concrete;
- a ready-made lightweight concrete mixture used in monolithic construction and for the production of wall blocks in a factory setting.

This structure allows for the phased organization of the production process and the creation of finished products for various applications.

The DLM is mixed with water in a mixing unit until a homogeneous concrete mixture is formed. After the finished mass is poured into molds, it is kept in a special chamber at a temperature of 25–30°C for 8 hours. In the next stage, the blocks are removed from the molds and

allowed to cure and harden in a warehouse for 7 days at a temperature of at least +15°C.

The dry mix for foam concrete was prepared in a SMV-3 laboratory vibratory ball mill, manufactured by "Qizilqumcement" JSC. The particle size distribution (PSD) was determined using a Horiba LA950 laser particle size analyzer.

Figure 2 illustrates the effect of the nanomodification process on the particle size distribution (PSD) of the mechanically activated dry mixes.

The particle size distribution graph of the dry mix prepared with PC500 D0 cement without a nanomodifier (Fig. 2-a) is observed to have a two-peaked, or bimodal, character. The main share of particles is concentrated in the 8–30 μm range, constituting approximately 59% of the total volume. The smallest particle size is 1.73 μm, while the largest is 394.24 μm.

The particle size distribution graph of the dry mix modified with the KZ-TM-30 nanomodifier exhibits a polymodal character (Fig. 2, b), with the overall

distribution shifted to the left, towards 0.1 μm . The volumetric particle distribution is as follows: grains in the 0.1–5 μm range constitute 34%, those in the 5–10 μm range make up 26%, the 10–20 μm range accounts for 33%, and particles larger than 20 μm comprise 7%. Such a particle size distribution structure leads to a rapid increase in strength when the dry mix is combined with water. This is because it is well-known that fine particles in the 0–5 μm range significantly influence the strength development of the cement matrix during the initial hours of the hardening process.

Based on the analysis of the obtained results, a modified dry mix composition (Table 1) was selected for preparing foam concrete with a density of 400 kg/m^3 and improved strength properties (Table 2). The main quality indicators of the dry mix are as follows:

- specific surface area – at least 450 m^2/kg ;
- mixing and setting time with water – not more than 5 minutes;
- mobility of the foam concrete mixture (according to the Suttard method) – 118–130 mm.

Table 1

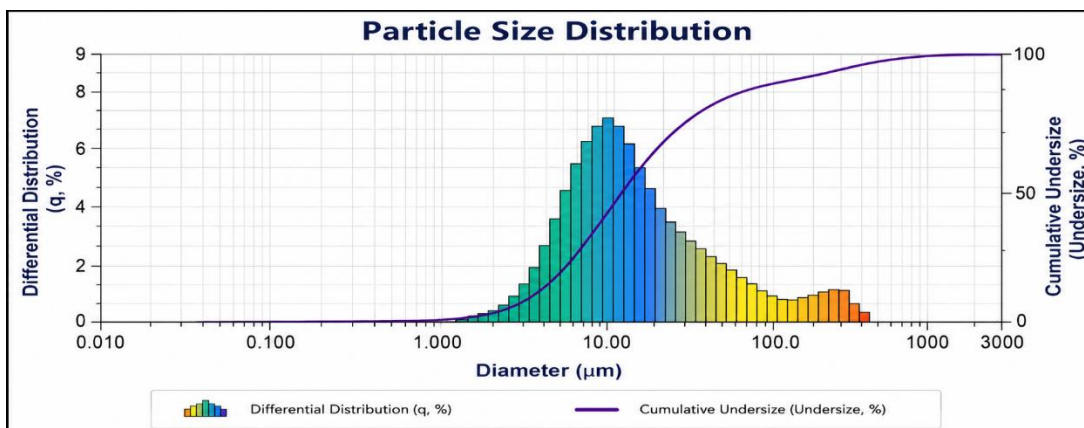
Composition of Dry Mixes for Foam Concrete

Brand of dry mix	Average density of foam concrete, kg/m^3	Material consumption for 1 ton of dry mix		
		Cement, kg	Kremnezol KZ-TM-30, kg	Foaming agent, l
Precast concrete panel system 400 – main	400	990	-	10
Precast concrete panel system 400 nanomodified	400	989,99	0,00982	10

Table 2

Compressive Strength of Foam Concrete Prepared from Dry Mixes

Material name	Average density, kg/m^3	Compressive strength, MPa	
		3 day	28 day
Foam concrete made from a dry mix	400	1,1–1,3	1,5–1,7
Foam concrete prepared from a nano-modified dry mix	400	1,5–1,6	1,9–2



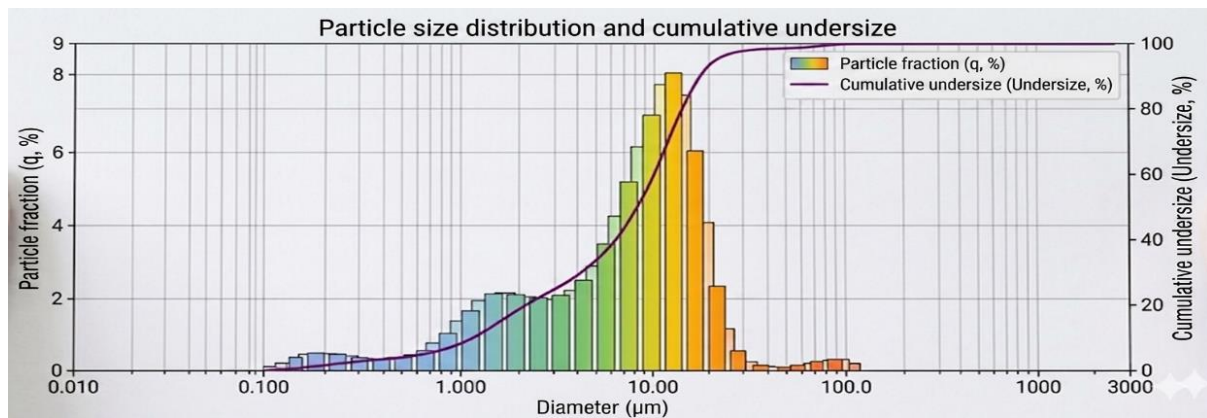


Figure 2. Particle size distribution: a) initial dry mix for foam concrete; b) modified dry mix for foam concrete

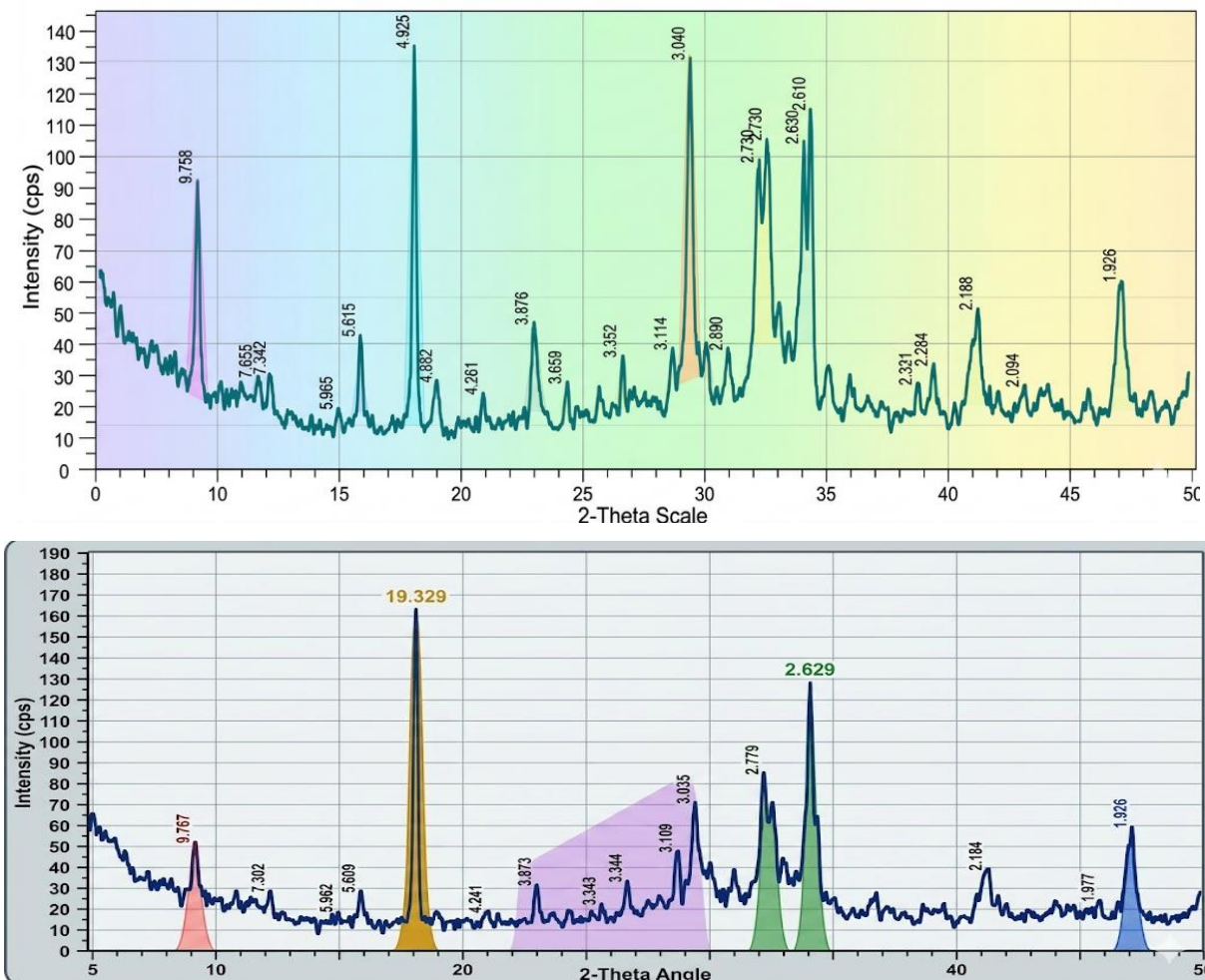


Figure 3. Diffractogram of foam concrete: a – from the base dry mix; b – from the modified dry mix

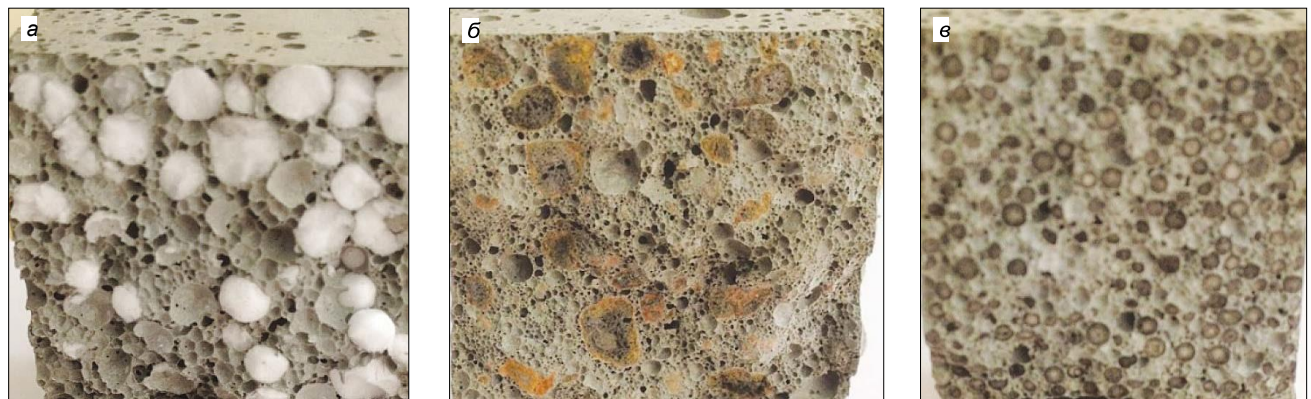


Figure 4. Fracture surface of the LPC sample: a – with expanded polystyrene; b – with expanded clay aggregate; v – with foam glass

Table 3

The Effect of Aggregate on the Strength of Lightweight Porous Concrete (LPC)

Filler	Aggregate size, mm	Compressive strength, MPa	Average density of UGB, kg/m³	28-day compressive strength, MPa	Design KKK (R/D) under compression	28-day flexural strength, MPa	Calculated bending stress-strain state
Local expanded clay aggregate (Akhangaran)	5–10	0,28	760	3,2–3,8	4,2–5,0	2,2	2,95
Local expanded clay aggregate	10–20	0,21	670	2,9–3,5	4,3–5,2	1,8	2,68
Foam glass gravel	0–2	2,70	560	4,8–5,4	8,5–9,6	1,55	2,77
Foam glass granules	0–5	2,35	510	4,0–4,6	7,9–9,1	1,38	2,70
Granulated foam glass	7–20	0,85	420	2,5–3,3	6,0–8,1	0,72	1,75
Expanded polystyrene granules	4–6	–	320	1,0–1,2	3,1–3,6	0,56	1,75

Table 4
Shrinkage of lightweight porous concrete

Ingredients	Settlement value, mm/m
D400 grade foam concrete made with local cement (Qizilqum Cement)	2,10
Lightweight concrete with D700–D750 grade expanded clay (based on Akhangaran expanded clay)	0,85
D400 grade foam-glass lightweight concrete	1,65
D450 grade foam glass dry-mix concrete	1,25
D500 grade lightweight aggregate concrete	1,32
D550 grade foam glass concrete	1,55
D300 grade polystyrene thermal insulation concrete	2,00
Combined lightweight concrete, grade D650, based on expanded clay and foam glass	1,10

X-ray fluorescence analysis was used to determine the mineralogical composition of cement stone with and without the KZ-TM-30 additive (Fig. 3).

Analysis of the data revealed that the main characteristic of the nano-additive sample, compared to the control sample, is an increase in the intensity of portlandite reflections (4.93; 2.63; 3.41; 1.93 Å) and a decrease in the reflections of anhydrous calcium silicates (2.7761; 2.785; 2.748 Å) and possibly (2.28; 2.32 Å). This indicates an activation of hydration processes in the sample with the additive, as the increase in free lime occurs due to the acceleration of the hydrolysis of

anhydrous calcium silicates, which contributes to a higher amount of Ca (OH) 2 in the cement system.

It should be noted that the intensity of calcite reflections is significantly higher in the control sample compared to the sample with the additive. This indicates a slowing of the carbonation processes and suggests that a portion of the Ca (OH) 2 in the additive-containing sample was not displayed on the radiograph and may also be bound with weakly crystallized, tobermorite-like calcium hydrosilicates.

Table 5
Frost Resistance of Porous Concrete

Ingredients	Frost resistance rating, in cycles	Standard measure of cold resistance
Foam concrete based on locally sourced D400 grade cement	40	In partial compliance with GOST 25485-89
Lightweight concrete, grade D700–D750, with expanded clay aggregate	50–75	F35–F50, in accordance with GOST 25820–2014
Lightweight concrete based on foam glass, grades D400–D500–D600	50	Satisfactory according to local test results.
D300 grade lightweight concrete with expanded polystyrene granules	15–25	F15–F25 per GOST 51263–2012
D650 grade combined lightweight concrete based on expanded clay and foam glass	75	Suitable for F50 level
D500 grade foam glass thermal insulation concrete	50	Recommended for the temperate, dry climate of Uzbekistan.

Another characteristic feature of the sample with nanoadditives is a significant decrease in the ettringite

reflections (9.73; 5.61; 4.69; 3.88; 2.209 Å) compared to the control sample. Although the reflection values for

calcium monohydrosulfoaluminate (2.06 \AA), which also belongs to this phase, are slightly higher for the control sample, this indicates that the formation of ettringite and its subsequent recrystallization into monosulfate are slowed in the presence of the nanoadditive.

It should be noted that if the 4.26 \AA reflection is attributed to gypsum dihydrate, its intensity is slightly lower in the sample with the nanocomposite additive. A portion of the gypsum may remain unbound in both the control sample and the sample with the additive. In the presence of the aluminate phase and calcite, it is likely that a portion of the free gypsum dihydrate will subsequently bind into the $3\text{CaO}\cdot\text{Al}_2\text{O}_3\cdot 3\text{CaSO}_4\cdot 32\text{H}_2\text{O}$ phase (ettringite analogue: $d = 9.41; 3.80; 2.70; 2.51 \text{ \AA}$).

In general, it can be concluded that the nano-additive accelerates the hydration process of cement systems, thereby increasing their strength. However, an increase in unbound free lime within the cement system is considered a negative factor. On the other hand, the decrease in ettringite content in the sample with the additive is a positive development, as it reduces the probability of a decrease in the structure's density that can result from the recrystallization of ettringite into calcium monohydrosulfoaluminate.

A macrostructural analysis of the developed lightweight polystyrene concretes (Figures 4 and 5) revealed that the filler is uniformly distributed throughout the sample, regardless of the granule type. No signs of stratification were detected, which can result from the density difference between the filler and the porous cement-sand matrix. Furthermore, the porous cells of the matrix are of a closed type. This feature demonstrates another significant advantage of the technology for preparing lightweight polystyrene concrete from a dry foaming mixture compared to traditional methods. The microstructure of the resulting lightweight concrete was analyzed in detail using an EMMA4 electron microscope.

The micrograph (Fig. 6) shows expanded clay granules of various sizes, their dense glass phase with predominantly cellular pores, and the cement stone in the contact zone. A dense layer of cement stone, approximately $50 \mu\text{m}$ thick, forms at the boundary with the expanded clay granule. The contact boundary between the cement stone and the aggregate granule is

dense, with no stratification, cracks, or other defects observed. The boundary between the foam glass (a porous-spherical dense matrix) and the cement stone (crystals and their "fragments") is also clearly visible. The contact between the polystyrene foam and the cement stone is also dense; defects on the surface of the granules are filled with cement stone, and there are no cracks or displacements.

Thus, in all cases where foam concrete is filled with porous spheres made of various materials such as ceramics, glass, and polystyrene, it forms a tight contact with the surface of the granules of the cement-sand mixture. The boundary layer does not exceed 50 microns, ensuring good adhesion of the cement-sand mixture to various types of porous granules.

The effect of the filler type on the strength indicators of lightweight concrete prepared based on KBQA is shown in Table 3.

The flexural strength of the LWC was only two times lower than its compressive strength. This indirectly indicates good adhesion of the porous aggregate to the foam concrete matrix, since the flexural adhesion strength in the optimal structure of LWC is directly dependent on the porosity of the aggregate's surface.

Table 4 presents the final shrinkage values of the samples after one year of drying. According to the data in Table 5, the addition of porous aggregates significantly reduces shrinkage compared to the control composition; for example, when using granulated foam glass, shrinkage decreases by up to 1.5 times.

The frost resistance grade of foam concrete and lightweight concrete is determined by the number of freeze-thaw cycles it can withstand. During this process, the loss in compressive strength of the foam concrete must not exceed 15%, and the loss in mass of the samples must not exceed 5%. The test results are shown in Table 5.

Adding expanded clay gravel and foam glass to the dry mix makes it possible to increase the frost resistance grade of the lightweight concrete from M35 to M50. Conversely, when expanded polystyrene granules are introduced, the frost resistance grade decreases from M35 to M10 due to the material having lower compressive strength compared to the foam concrete produced from the modified dry mix.

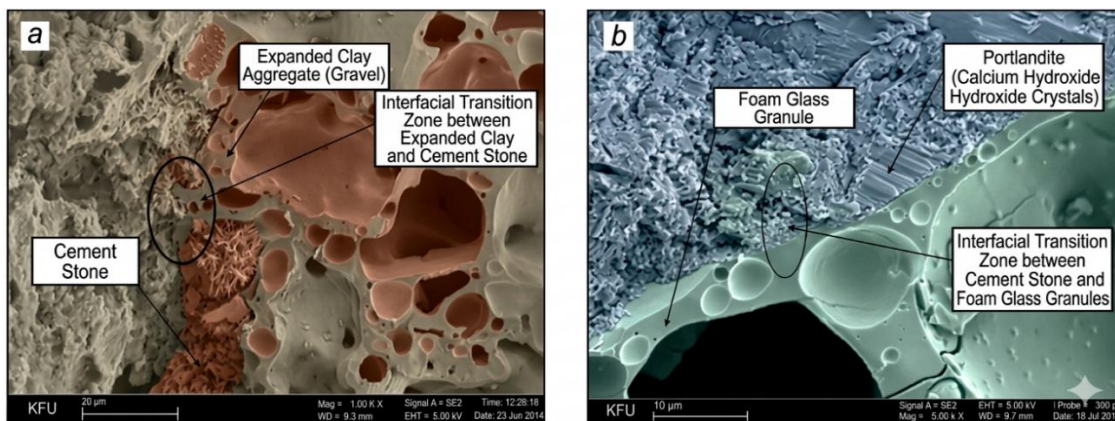


Figure 5. Microstructure of lightweight concrete prepared from a dry mix: a – expanded clay aggregate at 1000x magnification; b – granulated foam glass at 2000x magnification.

The thermal conductivity indicators for the developed lightweight concrete blocks are shown in Table 6. According to the data presented, the resulting concretes are classified as effective thermal insulation materials,

since their thermal conductivity coefficients are, on average, 20% lower than the standard values for the same density.

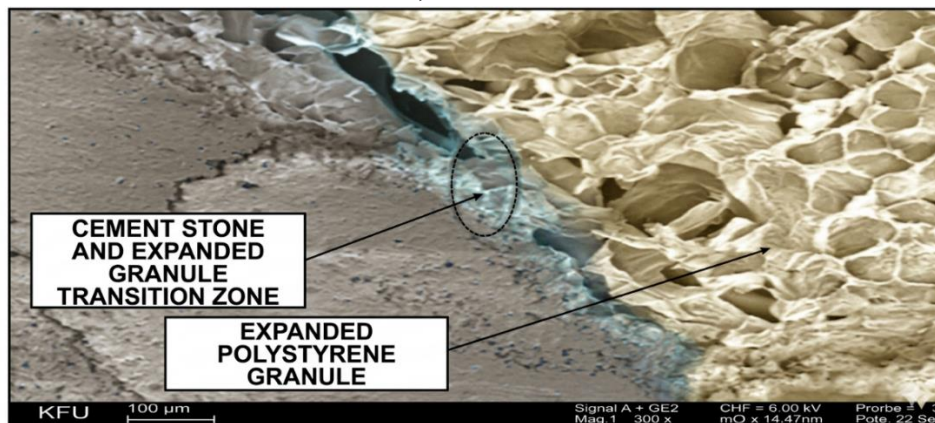


Figure 6. Microstructure of lightweight concrete made from a dry mix with expanded polystyrene granules, magnified 100 times.

The results of the vapor permeability study of the developed lightweight concretes are presented in Table 7. According to the data obtained, the materials have good vapor permeability and can provide a comfortable indoor microclimate when used in building wall structures. Thus, the physical and technical properties of the developed lightweight porous concrete compositions allow for their effective use in manufacturing wall blocks and monolithic enclosure structures for residential and administrative buildings.

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