БУДІВНИЦТВО ТА ЦИВІЛЬНА ІНЖЕНЕРІЯ

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Modified Cellular Concrete: Structure, Properties, and Potential Applications

The article proposes a method for the autoclave–free production of ultra–lightweight cellular concrete based on Portland cement, glass waste, and liquid glass. A hardening activator and a gas–forming agent are used to produce a porous material with high thermal insulation properties and water resistance. The proposed concrete can be used as thermal and sound insulation material, as well as for masonry and construction of non–bearing internal walls.

ellular concrete, waste glass, liquid glass, alkaline activation, porous structure, water resistance

Problem Statement. In the context of the need for conservation and efficient use of natural resources, special attention is given to the rational use of secondary materials in the production of construction products. The development of waste–free technologies and recycling contributes to improving the environmental situation and reducing the depletion of non–renewable resources. Glass waste is a large–volume secondary mineral resource whose recycling is a complex task. The disposal of glass negatively impacts the environment, as glass in landfills hinders soil reclamation. Therefore, finding new methods for utilizing glass waste is crucial.

Analysis of Recent Studies and Publications. Glass waste has been identified as an effective aggregate for building materials production. Ground glass is used in foamed glass, ceramic products, facade cladding, thermal insulation materials [1], cement mixtures, and geopolymer concretes. Research [2] shows glass's potential in road construction, including asphalt mixtures and road coverings , as well as improving road markings with glass beads. Ground glass is particularly promising for porous thermal insulation materials and aerated concrete, as it is less flammable than traditional insulation materials like polyurethane, polypropylene, and polystyrene [3]. However, fibrous mineral materials such as glass wool do not fully protect metal structures from corrosion without additional waterproofing.

Studies [4–5] highlight the high thermal conductivity of porous cement materials with artificial aggregates, but research [6] shows that temperature reduction can be achieved using liquid glass as an activator for slag mixtures. Moreover, liquid glass mixtures set at high temperatures and altered pH.

Problem Statement. Thus, despite the considerable number of studies conducted, the issue of obtaining porous materials based on glass and liquid glass, as well as investigating their properties, remains insufficiently explored. Therefore, the aim of this work is to determine the optimal conditions for forming a porous structure of foam concrete made from glass waste and liquid glass. This is an important step in the development of new, more efficient, and environmentally safe building materials.

Main Material Presentation: For the production of cellular concrete, the following materials were used: glass waste, liquid glass, sodium hydroxide, sodium hexafluorosilicate, Portland cement, and water.

Aluminum powder was used as a gas–forming agent. The chemicals had a purity grade of "chemical purity" and were used without additional purification[7].

Glass Waste**:** Uns sorted glass waste with a fineness modulus (Fm) of 0.945, true density of 2435 kg/m³, and bulk density of 1313 kg/m³ was used in the work. Part of the glass waste was ground to a powdery state to achieve a specific surface of 450–550 m²/kg. The grinding time to achieve the specific surface of the ground glass (450–550 m²/kg) was 40–60 minutes. The average chemical composition of the glass waste used is provided in Table 1.

Table 1 – Chemical composition of cullet used in the work.

Oxide	SiO_2	Al_2O_3	Fe_2O_3	CaO+MgO	Na_2O+K_2O	SO_3
Content, mass.%	71.5–72.6	2–2.6	0.1–0.25	10–10.5	15.0–16.0	0.3–0.4

Source: developed by the author

Liquid Glass**:** Sodium liquid glass was used, which is an alkaline aqueous solution of sodium silicates ($Na_2O \cdot nSiO_2$) with a mass fraction of SiO_2 ranging from 22.7 to 29.6%, a silicate modulus (n) between 2.3 and 2.6, and a density of 1360–1450 kg/m³.

Aluminum Powder**:** To form the porous structure of concrete using glass as an aggregate, aluminum powder of grade PAP–1 was used as a gas–forming agent. The residue on sieve № 008 was 1%. The powder contains impurities in mass %: iron — 0.5, silicon — 0.4, copper — 0.05, manganese — 0.1, moisture — 0.2, oil — 3.8. Sodium hexafluorosilicate Na2SiF6 was used as a gas formation accelerator and hardener.

Purity of Reagent**:** 98 mass % Na_2SiF_6, insoluble residue no more than 1 mass %, water content no more than 0.5 mass %. Sodium hydroxide NaOH used in the study contained at least 99% NaOH, with a mass fraction of sodium carbonate (Na_2CO_3) not exceeding 0.8 mass %.

Portland Cement**:** To ensure strength and improved water resistance of pore walls in the porous material, Portland cement CEM I 42.5 R (EN 197–1) was used, containing tricalcium silicate not less than 60 mass % and tricalcium aluminate not more than 9 mass %; the specific surface area of the cement was 300–400 m²/kg. Water**:** Distilled water was used to prepare the mixtures.

Mechanical Testing of Samples: Compression and bending tests of glass–filled samples were conducted in accordance with European standards [8-9]. The samples for compression strength tests had a cubic shape with a side of 10 cm, and for bending strength tests, they had a beam shape of 10 × 10 × 36 cm³. The samples were cut from control blocks with dimensions of 20 × 40 × 40 cm³. Control blocks were prepared by filling the molds with approximately 1/3 volume of a well–mixed component mixture, holding the mixture until the end of the foaming process, and then removing the blocks after 3 days of storage at 20 ± 2°C. The blocks were then wrapped in polyethylene film and stored under the same conditions for 28 days. Prior to testing, the samples were dried at 60°C to a constant weight. Compression and bending tests were performed using presses with a loading rate of 0.05 kN/s. Each sample of the same composition was tested six times, and the average strength values were calculated from the results.

Specific Surface (Ssp)**:** The specific surface of materials with developed microstructures and porosity was determined by the Brunauer–Emmett–Teller (BET) method.

The determination was based on experimental data from low–temperature nitrogen adsorption at 77 K, building adsorption isotherms.

Thermal Analysis**:** Thermal transformations during heating of the materials were studied using differential thermal analysis (DTA) and thermogravimetric analysis (TG). The samples were heated in alumina crucibles with an airflow rate of 100 mL/min and a heating rate of 10 K/min.

Sample Porosity**:** The porosity of the samples was calculated using experimentally determined values of true density and average density ρ□ in a dry state, applying the corresponding formula for determining porosity P (%) [10].

$$P = \left(1 - \frac{\rho_0}{\rho}\right) \cdot 100\% \quad (1)$$

Open porosity P_{op} (%) is determined by the following formula:

$$P_{op} = W_o \quad (2)$$

where W_0 – is the water absorption of the material by volume, %

The closed porosity P_C (%) was calculated using the following formula:

$$P_c = P - P_{op} \quad (3)$$

The normal density of the samples was calculated using the following formula:

$$\rho = \frac{m}{V} \quad (4)$$

The production of cellular concrete containing cullet typically involves autoclave processing [11]. The key process in this treatment is the formation of insoluble silicates, especially in mixtures with at least 15% alkaline oxides. In this study, to improve energy efficiency, liquid glass was used instead of autoclave treatment. Due to its high modulus (n = 2.3–2.6) and increased viscosity, water was added to the mixture to enhance the porosity of the final material. Another important factor influencing the properties of the resulting cellular concrete is the dispersion of the glass.

Unsorted cullet, which is rarely used in glass factories due to its impact on the homogeneity and quality of the final glass products, was used here. However, for producing non–combustible porous materials containing cement, glass homogeneity is not critical, allowing for the use of cullet with varying chemical compositions and dispersions. The cullet was degreased in acetone, washed with distilled water, and dried at room temperature before being ground in a screw crusher to achieve the following characteristics: fineness modulus (Fm) = 0.945, true density of 2435 kg/m³, and bulk density of 1313 kg/m³. To optimize the packing density of the raw material grains and form a dense, strong structure, the proportion of large and small fractions of the ground cullet was balanced. The finely ground cullet serves as a structuring material due to the interaction of its amorphous silicon dioxide (SiO□) with the alkaline environment of liquid glass and Portland cement, which affects the strength of the pore walls. To increase the fine fraction, part of the ground cullet was milled into powder to achieve a specific surface area of 450–550 m²/kg. The granulometric composition of the ground and milled cullet is shown in Table 2, and the particle size distribution is presented in Fig. 1.

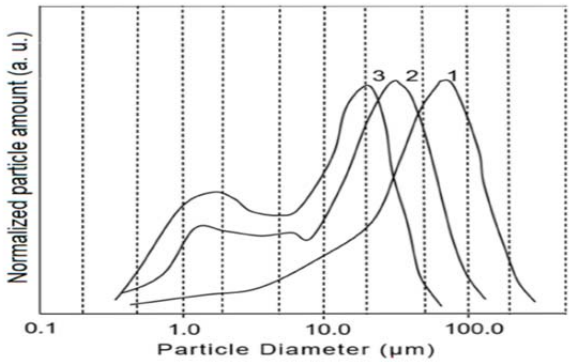


Figure 1 – Size distribution of glass particles with different specific surface area: (1) Ssp = 450 m^2/kg;(2) Ssp = 500 m^2/kg; (3) Ssp = 550 m^2/kg.

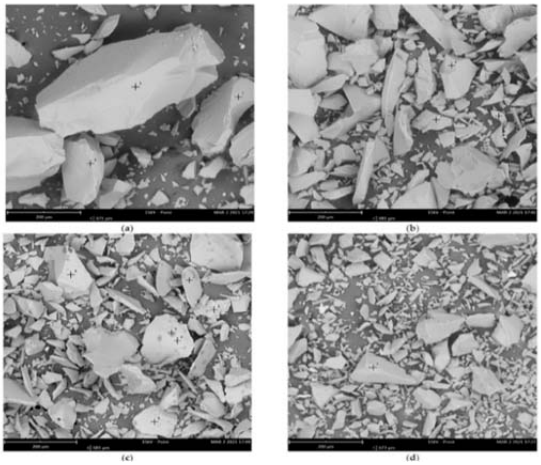
Source: developed by the author

Table 2 – Fractional composition of coarse crushed and highly dispersed milled cullet.

Particle Size	Mass Fraction, wt.%			
	Coarse Cullet	Milled Cullet, Ssp = 450 m^2/kg	Milled Cullet, Ssp = 500 m^2/kg	Milled Cullet, Ssp = 550 m^2/kg
d > 1 mm	10.5	0	0	0
0.2 < d < 1.0 mm	21.5	5.2	1.7	1.9
0.063 < d < 0.2 mm	49.3	76.1	89.7	91.3
d < 0.063 mm	13.2	18.7	8.6	6.8

Source: developed by the author

Electron microscope analysis revealed the irregular shape of the glass cullet particles (Fig. 2). Using light scattering dispersion, the particle size characteristics were determined: volumetric D43, surface D32, and arithmetic D10 equivalent diameters. Ground glass with Ssp = 450 m²/kg (Table 3) was used.



(a) large–fraction cullet; (b) ground cullet with Ssp = 450 m2/kg; (c) ground cullet with Ssp = 500 m2/kg; (d) ground cullet with Ssp = 550 m2/kg.

Figure 2 – Microphotographs of particles of various size fractions of waste glass

Source: developed by the author

Table 3 – Fractional composition of coarse crushed and highly dispersed milled cullet.

Sample	Glass Particle Size, μm					
	Volume Mean D43		Surface Mean D32		Arithmetic Mean D10	
	μm^3	Ratio to the Reference Sample	μm^2	Ratio to the Reference Sample	μm	Ratio to the Reference Sample
Milled cullet Ssp = 450 m^2/kg	46.68	–	19.21	–	15.45	–
Milled cullet Ssp = 500 m^2/kg	22.77	2.05	11.43	1.68	12.16	1.27
Milled cullet Ssp = 550 m^2/kg	22.34	2.09	11.08	1.73	11.61	1.33

Source: developed by the author

Previous study [12] showed that to obtain cellular concrete with acceptable strength properties under natural curing conditions, certain component ratios must be followed: liquid glass 28–32 wt.%, poly–disperse glass cullet 38–47 wt.%, Portland cement 9–12 wt.%, sodium hexafluorosilicate 3.5–4.5 wt.%, sodium hydroxide 2.5–3.5 wt.%, aluminum powder 1–1.2 wt.%, water 8–9 wt.%. During the preparation of the cement paste, liquid glass and water are added to the mixture, initiating exothermic reactions and raising the mixture temperature to 80–100 °C. The formation of a porous structure and hardening lasts 20–40 minutes, after which the material cools and does not require further thermal treatment. Changes in the component ratios significantly affect the strength and structure of the resulting material.

The effect of Ssp glass waste on the strength of cellular concrete was studied on samples containing 40 wt.% cullet, 30 wt.% liquid glass (ρ = 1300 kg/m³), 12 wt.% Portland cement, 4.3 wt.% sodium hexafluorosilicate, 3.5 wt.% sodium hydroxide, 1.2 wt.% aluminum powder, and 9 wt.% water. The results showed that the compressive and bending strength increases with the increase in the specific surface area of milled glass to 450–550 m²/kg (Fig. 3). The increase in dispersion contributes to a higher reactivity of the particles, which enhances the formation of silicate structures under the influence of an alkaline environment.

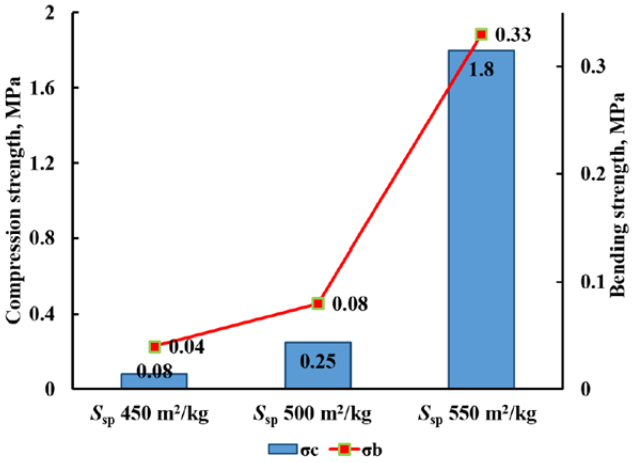
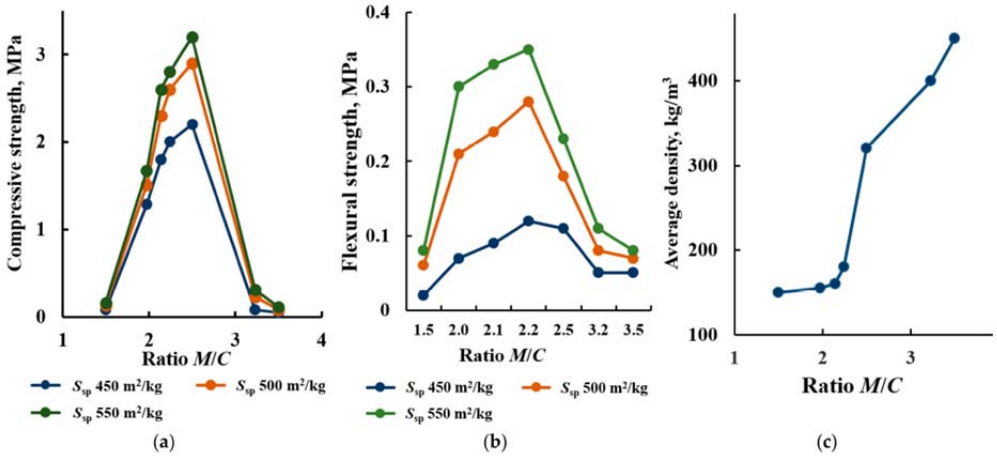


Figure 3 – Dependence of the strength of cellular concrete samples based on waste glass and liquid glass on the specific surface area of milled glass

Source: developed by the author

Sodium aluminate formed in liquid glass in the presence of calcium hydrosilicates promotes the formation of insoluble aluminosilicates, such as Na□O·Al□O□·6SiO□ and Ca[Al□Si□O□], stabilizing the pore wall structure in the final material. The reaction of amorphous silica with liquid glass at the "solution–particle" interface is accompanied by polymerization processes, which strengthen the bond between glass particles by forming three–dimensional silicate structures. The optimal ratio of finely ground to coarsely ground cullet for achieving maximum strength is 1.97–2.24, which provides strong samples with a dry bulk density ranging from 150 to 300 kg/m³ (Fig. 4).

Both high and low content of large glass cullet fractions fail to achieve adequate strength in the samples. With low crushed glass content, the density of the samples increases significantly, but they become brittle. The glass fraction ratio also affects the thermal conductivity of the cellular concrete samples: as the ratio increases from 1.5 to 3.5, thermal conductivity reaches its maximum. Phase transitions during heating were evaluated using differential thermal analysis. After drying, hydrated structures with small amounts of crystallization water remain, with water loss occurring between 100–150 °C.



(a) – compressive strength; (b) – flexural strength; (c) – density

Figure 4 – Dependence of compressive strength (a), flexural strength (b) and density (c) of glass–filled cellular concrete samples in the dry state with a density of 360 kg/m3 on the mass ratio of finely milled and crushed glass

Source: developed by the author

With temperature increase from 150 to 550 °C, polycondensation processes occur in the pore wall structure, accompanied by water loss of 3–5%. In this range, dehydration of hydro–silicates takes place. As the temperature increases from 550 to 850–950 °C (ascending exothermic peak), crystallization of liquid glass and finely milled glass cullet occurs, with an exothermic peak of 7–9 mW/mg without mass loss. Polymorphous transformations of calcium silicates also happen in this range. Higher temperatures lead to melting of the samples above 900 °C. Increasing the finely milled glass proportion reduces the upper temperature limit range from 800 to 400 °C, as phase transformations in samples with finely milled glass occur at lower temperatures.

Thus, glass dispersion significantly affects pore wall strength in porous concrete. The highest strength is achieved with a milled–to–crushed glass ratio of 1.97–2.24. In this case, small glass particles form the polymeric silicate bond, while large particles act as reinforcements.

The density of liquid glass affects hydration intensity, setting time, and strength of the resulting porous material. The liquid glass density used ranged from 1130 to 1350 kg/m³.

Increasing liquid glass density increases both the density and strength of the cellular concrete. Strength depends linearly on the liquid glass density between 1200–1350 kg/m³, but at higher densities, strength increases more slowly due to high viscosity, impairing gas formation. At lower liquid glass densities (1130–1200 kg/m³), it's impossible to achieve a strong porous structure, with pore walls breaking under slight mechanical impact.

Increasing water content in low–density liquid glass decreases pH, reducing amorphous silica dissolution intensity and material strength. Therefore, the optimal liquid glass density is between 1230 and 1350 kg/m³, allowing for the production of low–density products with sufficient strength.

The porosity of cellular concrete is characterized by pore content, diameter, and uniformity of distribution. Macropores with diameters of 1 mm or more are formed due to gas formation. In systems with macropore volumes over 50%, porosity can exceed 90%, with the pore wall material occupying a smaller area.

For foam concrete samples based on glass, compositions were selected with a finely milled–to–crushed glass ratio of 2.24, and liquid glass density between 1130 and 1350 kg/m³. The macro– and microstructure of the samples were evaluated using electron microscopy, and macroporosity was measured microscopically. The results of macroporosity measurements based on liquid glass density are presented in Table 3.

Table 3 – Macroporosity of glass–filled aerated concrete samples at different densities of liquid glass.

No	Liquid Glass Density, kg/m^3	Total Porosity, %	Open Porosity, %	Closed Porosity, %
1	1350	68.7	14.63	54.07
2	1310	73.5	10.05	63.45
3	12301	78.9	10.77	68.13
4	1200	82.4	10.72	71.68
5	1130	85.6	8.90	76.7

Source: developed by the author

Cellular concrete samples exhibit high porosity with mostly closed pores, resulting in low thermal conductivity. The pore shape is nearly spherical, and their diameter varies with material density. At densities of 280–300 kg/m³, pores measure 650–850 μm, while at higher densities, they shrink to 350–600 μm. Pore size distribution curves were plotted, and calculations for mean pore diameters (arithmetic and volumetric) and sample polydispersity (P = dN/dV) were performed. Lower–density samples have less homogeneous structures, while higher–density samples are more uniform.

The pore walls exhibit a spongy structure typical of hardened gels. Adsorption measurements reveal polymer adsorption in small pores, while capillary condensation occurs in mesopores (1.5–2 nm in size) within the pressure range of 0.5–0.95.

Water absorption tests show that the material has high porosity, with water absorption by weight ranging from 36 to 38.5%. Water absorption is more stable when liquid glass density is between 1200–1310 kg/m³. Outside this range, the porous structure changes, affecting water absorption. Higher–density liquid glass (1350 kg/m³) results in more macro and mesopores, increasing volumetric water absorption.

Despite high water absorption, the samples retain strength when saturated, showing high water resistance due to the material's hydrophobic properties. Water absorption and resistance depend on the porous structure and raw material ratios.

Compared to other construction materials, this cellular concrete belongs to the lightest cementitious group. Its compressive strength (up to 2 MPa) makes it suitable for non–load–bearing applications. It is not ideal for high–humidity or structural use due to its water absorption and low strength but works effectively as a thermal insulator. It can be used in non–load–bearing interior walls and infill masonry. The formation process also allows flexibility in product shapes and sizes without the need for formwork.

Conclusions. The production of ultra–lightweight cellular concrete based on glass, Portland cement, liquid glass, and an activator for mixing components has been proposed. This initiates complex hydrolytic and gas–forming exothermic reactions, leading to the formation of a porous structure within 20–40 minutes without additional thermal treatment. Depending on the composition and dispersion of the components, an average density of 150–320 kg/m³, compressive strength up to 2.0 MPa, and thermal conductivity coefficient of 0.05–0.09 W/(K·m) are achieved. Optimal characteristics are achieved with a ratio of fine to coarse glass of 1.97–2.24.

The mechanism for forming a strong porous structure lies in the partial dissolution and subsequent joint hardening of layers at the "solution/glass particle" boundary due to the formation of a three–dimensional structural foundation. This ensures structural stabilization due to reinforcement with large glass particles and the formation of insoluble compounds. A comparison of the properties of the obtained material with known data shows that it can be used as a thermal and sound insulation material, as well as for filling masonry and constructing non–load–bearing interior walls. It offers advantages such as energy–saving production technology, resource efficiency due to the use of glass as a raw material, and high fire resistance.

References

1. Popovych, O. R., Zakharko, Ya. M., & Malovanyi, M. S. (2013). Problemy utylizatsiyi ta pererobky budivel′nykh vidkhodiv [Problems of utilization and processing of construction waste]. *Visnyk Natsional'noho universytetu "L'vivs'ka politekhnika"*. Teoriya i praktyka budivnytstva, (755), P. 321–324 [in Ukrainian].
2. Dobrotvor, A. A. (2024). Napryamky vykorystannya vidkhodiv znesennya ta ruyinatsiyi v budivel′niy haluzi [Directions for using demolition and destruction waste in the construction industry] [in Ukrainian].
3. Pyatnychuk, T. V., Gomenyuk, D. V., & Zaslavska, S. I. (2024). *Zbirnyk osvitnikh keysiv z enerhoefektyvnosti ta bezpeky pratsi v povoyennomu budivnytstvi: praktychnyy posibnyk* [Collection of educational cases on energy efficiency and labor safety in post-war construction: A practical manual] [in Ukrainian].
4. Boyko, V. O. (2024). Doslidzhennya skladu vysokomitsnoho betonu z skloboyu ta udoskonalennya tekhnolohiyi yoho pryhotuvannya [Investigation of the composition of high-strength concrete with cullet and improvement of its preparation technology] [in Ukrainian].
5. Kondrashchenko, O. V. (2007). Materialoznavstvo: Navchal′nyy posibnyk [Material Science: A textbook] [in Ukrainian].
6. Tatarenko, V. P. (2023). Pokrashchennya vlastyvostey nizdryuvatykh betoniv za rakhunok modyfikatsiyi yikh skladovykh [Improving the properties of cellular concrete through the modification of its components] [in Ukrainian].
7. Abd El-Fattah, Z. M., Ahmad, F., & Hassan, M. A. (2017). Tuning the structural and optical properties in cobalt oxide-doped borosilicate glasses. *Journal of Alloys and Compounds, 728*, P. 773–779. https://doi.org/10.1016/j.jallcom.2017.09.123
8. Akkurt, I., Gunoglu, K., Kurtuluş, R., & Kavas, T. (2021). X□ray shielding parameters of lanthanum oxide added waste soda□lime glass. *X□Ray Spectrometry, 50*(3), P. 168–179. https://doi.org/10.1002/xrs.3142
9. Liu, Y. L., Liu, C., Qian, L. P., Wang, A. G., Sun, D. S., & Guo, D. (2023). Foaming processes and properties of geopolymer foam concrete: Effect of the activator. *Construction and Building Materials, 391*, 131830. https://doi.org/10.1016/j.conbuildmat.2023.131830

10. Berezovskyi, A. I., Sidnei, S. O., & Rudesko, I. V. (2019). Otsinka efektyvnosti materialiv dlya hermetyzatsiyi pustot budivel′nykh konstruktsiy [Evaluation of the effectiveness of materials for sealing voids in building structures] [in Ukrainian].
11. Herasyutenko, S. I. (2023). Analiz vplyvu disperhuyuchykh dobavok na vlastyvosti hazobetonu [Analysis of the effect of dispersing additives on the properties of gas concrete] [in Ukrainian].

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Модифікований ніздрюватий бетон: структура, властивості та потенційні сфери застосування

Використання відходів у виробництві будівельних матеріалів є одним із можливих рішень проблеми сталого управління непереробними відходами та вторинними ресурсами, що важко утилізуються. У цьому дослідженні запропоновано метод безавтоклавного виготовлення ніздрюватого бетону на основі портландцементу, склобою та рідкого скла. Як активатори тверднення використано гексахлоросилікат і гідроксид натрію, а газоутворювачем слугує алюмінієвий порошок. Тверднення сирих сумішей відбувається завдяки екзотермічному тепловиділенню, зумовленому комплексом хімічних реакцій у системі, що усуває потребу в додатковій термічній обробці. Для досягнення прийнятної міцності матеріалу оптимальним є використання двох фракцій склобою: грубодисперсного (модуль крупності Fm = 0,945) та дрібнодисперсного (питома поверхня Ssp = 450–550 м²/кг). Дрібні скляні частинки разом із портландцементом беруть участь у гідролітичних і структуроутворювальних процесах, тоді як грубі частинки виконують функцію армувального наповнювача.

У ході дослідження визначено вплив дисперсності скла та густини рідкого скла на густину, пористість, міцність, водопоглинання та водостійкість отриманого пористого матеріалу. Для ніздрюватого бетону із середньою густиною у сухому стані 150–320 кг/м³ отримано такі характеристики: міцність на стиск до 2,0 МПа, міцність на вигин до 0,38 МПа, коефіцієнт теплопровідності 0,05–0,09 Вт/(К·м) і максимальна робоча температура 800°С. Запропонований ніздрюватий бетон може використовуватися як негорючий тепло- та звукоізоляційний матеріал. Крім того, блоки з ніздрюватого бетону придатні для заповнення кладки та зведення ненесучих внутрішніх стін, забезпечуючи переваги у сфері енергоефективного виробництва та переробки ресурсів.

ніздрюватий бетон, склобій, рідке скло, безавтоклавне виробництво, пористі матеріали, теплоізоляція, легкий бетон

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