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Geopolymer porous concrete: formation and performances

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ABSTRACT
The article presents the results of geopolymer technology development and a study of the performance of lightweight concrete based on a porous aggregate. The purpose of the study is to identify the transformations in composition and structure during the formation and operational testing of porous geopolymer concrete. The porous aggregate and binder are synthesized from molding mixtures of related composition containing sodium liquid glass and finely dispersed from thermal power plants' waste (fly ash and aluminosilicate microsphere). A thermal curing mode for concrete is proposed to ensure the formation of a porous structure with satisfactory resistance to mechanical stress and water. Phase transformations are studied during thermal synthesis of geopolymer material, with prolonged exposure of concrete to water and solutions of magnesium sulfate and sodium. Preliminary economic calculations are performed, indicating the advantages of porous geopolymer concrete compared to cement concrete based on expanded clay. The porous concrete based on geopolymer binder is intended for the production of energy-efficient wall products.

Keywords: Geopolymerization, liquid glass, large-porous concrete, fly ash, salt aggression.

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Introduction

The widespread use of concrete in construction is due to the possibility of regulating the composition and structure of concrete mixtures, using raw materials of various origins. The predominance of cement concretes is due to the deep study of the technology of production of concrete products, high construction and technical properties, and long-term observations of the performance of cement paste [[1], [2], [3]].

The cement industry is a major consumer of raw materials, fuel, and energy. Cement production accounts for about 5% of global CO_2 emissions [[4], [5]]. To solve this problem, the development of low-carbon concrete technologies is relevant. The use of low-clinker and cement-free binders contributes to achieving carbon neutrality of concrete [[6], [7], [8]].

Geopolymer concretes based on cementless binders obtained from powdered aluminosilicate and/or silicate material and a liquid alkaline component are very promising. Finely ground materials are used as a powder base for geopolymer binder, such as blast furnace slag, ash from fuel combustion, and agricultural waste, red mud, man-made glass [[9], [10], [11], [12], [13], [14]]. Hardening of geopolymer binders is based on chemical reactions between aluminosilicates and/or silicates and an alkali solution. Sodium (potassium) hydroxide and sodium (potassium) silicate or their combinations are used for alkaline activation of the powdered component of geopolymer binders [[15], [16], [17]].

The mechanism of geopolymerization is due to the processes of dissolution-hydrolysis and hydrolysis-polycondensation. Alkaline activation leads to the dissolution of silicon and alumina from powdered materials with subsequent orientation, polycondensation, and the formation of a three-dimensional rigid network and a ring structure with Si-O-Al-O bonds [[18], [19]]. Hydrates of various structures are involved in the formation of three-dimensional rigid networks: amorphous phase (geopolymer gel), semi-crystalline phases, and crystalline zeolites. The main gel-like hydration products of geopolymer binder are calcium aluminosilicate hydrate (C-A-S-H) and sodium aluminosilicate hydrate (N-A-S-H) [20]. High

mechanical properties of geopolymer concrete are achieved by selecting a rational proportion of sodium silicate and sodium hydroxide in the liquid component of the binder, as well as the ratio of silica and alumina in its solid part [[18], [19], [20]]. For example, geopolymer systems characterized by molar ratios of SiO_2/Al_2O_3 = 3.5 – 4.5; Na_2O/Al_2O_3 = 0.8 – 1.6; Na_2O/SiO_2 = 0.20 – 0.48 and H_2O/Na_2O = 10 – 25 have high strength and durability [21]. To ensure the required SiO_2/Al_2O_3 ratios in the geopolymer binder, combined powdered aggregates are used, for example, fly ash, blast furnace slag, and nickel slag with a high magnesium content [6]; liquid crystal glass waste and metakaolin [10]; glass powder, fly ash, and metallurgical slag [22]. The choice of the H_2O/Na_2O ratio determines the hardening capabilities of the binder, for example, for some systems at H_2O/Na_2O exceeding 25, polycondensation does not occur and the material does not harden [21]. The use of liquid glass with a high silica modulus, for example, 2.92, improves the rheological (fresh) and mechanical properties of self-compacting geopolymer concrete [23]. Along with the binder material composition, the curing conditions affect the geopolymerization reaction. When the curing temperature increases from 20 to 50 – 80°C, the activation of the binder accelerates, and the strength of the concrete increases twofold. Geopolymer binder containing metakaolin and subjected to multi-hour heat treatment at a temperature of 80°C, at the age of 56 days is characterized by a compressive strength of 67 MPa [13]. According to [23], geopolymer concrete based on fly ash demonstrates higher strength at temperatures of 150°C and 450°C.

The results of numerous studies confirm that geopolymer concrete can serve as a worthy alternative to cement concrete [[10], [13], [23]]. The widespread use of technogenic materials in geopolymerization processes indicates the resource-saving and environmental focus of cement-free concrete activated by alkali. Compared to Portland cement, the production of geopolymer binder emits 5 – 7 times less CO_2 [10].

Liquid glass is an alkaline component of many geopolymer binders. Liquid glass is an aqueous solution of alkali silicates. Sodium liquid glass ($Na_2O{\cdot}mSiO_2 + nH_2O$) is often used in geopolymer binders. Changing the ratios $(mSiO_2)/Na_2O$ and $(Na_2O{\cdot}mSiO_2)/H_2O$ allows to regulate the chemical activity and density of liquid glass.

High thermal sensitivity to thermal effects is an advantage of liquid glass [[23], [24]]. Solid foam with a density of 50 – 150 kg/m^3 is formed when liquid glass is heated to a temperature of 120 – 500°C. The combination of liquid glass with powder aggregates allows the creation of highly porous materials. The main driving force of the process of thermal porization of liquid glass compositions is an increase in the water vapor pressure with an increase in the temperature inside the liquid glass mass. According to [24], porization consists of three stages, the duration and nature of which depend on the type and amount of moisture. At the first stage (temperatures of 100 – 120°C), the original mass partially passes into a pseudopyroplastic state and begins to deform with an increase in volume. At the second stage (temperatures of 130 – 150°C), free and adsorbed moisture are vigorously released, and intensive porization of the material is observed. At the final stage (temperature above 150°C), the constitutional moisture is removed, the final restructuring of the structure occurs, and the physical and chemical processes are completed. The greatest contribution to the formation of the porous structure is made by the constitutional water, which begins to be removed at temperatures above 150°C. The unique properties of liquid glass form the basis of porous concrete technologies, granulated materials for various purposes [[25], [26]]. The multifunctionality of liquid glass is realized in the production of geopolymer concrete components: for alkaline activation of cementless binders and as part of the raw mix for porous granulated aggregates [[26], [27], [28]].

The diversity of the composition of binders and structures of geopolymer concretes predetermines their widespread use in energy-efficient construction. This requires the expansion of scientific understanding of the formation and stability of porous geopolymer concretes in various conditions [[29], [30], [31]].

The aim of the work is to study the transformations of the composition and structure during the formation and operational testing of porous geopolymer concrete.

The object of the study is geopolymer concrete based on a porous aggregate.

The idea of the study is the formation of a stable highly porous structure of geopolymer material due to components contributing to the directed creation of pores and voids.

Experimental part

To implement the idea, molding mixtures of liquid glass and fine-dispersed hollow waste from thermal power engineering were used. The use of

fine-dispersed waste from thermal power engineering in the composition of concrete is known and confirmed by positive experience [[9], [28]].

Geopolymer binder and porous concrete were synthesized from molding mixtures of related composition (Table 1). Sodium liquid glass with a silicate modulus n = $mSiO_2/Na_2O$ = 2.8 and a density of 1350 kg/m^3 was used in the experiments. Liquid glass is a binding base for molding compositions. When liquid glass is heated, steam is formed, which causes the pyroplastic raw material to swell.

Table 1 – Composition of molding mixtures

Raw materials	Content in molding mixture, kg/m^3	
	for geopolymer binder	***for porous aggregate***
Sodium liquid glass	200.0	136.0
Fly ash	85.0	40.8
Aluminosilicate microsphere	85.0	95.2

Chemical composition of thermal power plant fly ash, %: SiO_2 – 51; Al_2O_3 – 27; Fe_2O_3 – 4; CaO – 7; MgO – 2; Na_2O – 1; SO_3 – 2; LOI – 6. The material composition of fly ash includes aluminosilicate glass, quartz, mullite, and particles of unburned coal. The fly ash bulk density is 720 kg/m^3. The specific surface area of fly ash is 300 m^2/kg and does not require preliminary preparation of the material when introducing it into the molding mixture. The fly ash regulates the consistency of liquid glass molding mixtures and is active in geopolymerization processes. The low bulk density of fly ash is favorable for obtaining porous concrete. The use of fly ash helps to reduce thermal conductivity and increase the fire resistance of the material.

Chemical composition of ash aluminosilicate microsphere, %: SiO_2 – 68; Al_2O_3 – 25; Fe_2O_3 – 2; CaO – 5. Aluminosilicate microsphere consists of hollow glass-crystalline particles with a diameter of 50 – 200 μm. The microsphere is predominantly composed of aluminosilicate glass, and anorthite, mullite, and quartz are also present. Bulk density is 400 kg/m^3. Aluminosilicate microsphere serves as an elementary cell for the formation of a homogeneous porous structure of materials. The use of microsphere as an aggregate in concrete is due to its high dispersion, low density, high strength, increased resistance to thermal and aggressive effects.

The generally accepted methods were used to study the materials. A FSH-6K photosedimentometer was used to assess the dispersion of thermal energy waste. A hydrometer was used to determine the density of the liquid glass. To assess the overall porosity of the granules, the average density of both the starting material and the burnt granules was determined. The splitting method, taking into account the maximum force and the granule splitting area, was used to assess the strength of the fired granules. The arithmetic mean of the results of 10 tests on a PGM-1000MG4 hydraulic press was used to evaluate the granules' compressive strength.

The mass of the initial sample and the sample soaked in water for 1 day was compared to assess the water absorption of concrete.

The effect of liquids on the strength of the concrete under study was characterized by the coefficient of water resistance. For this purpose, the strength of concrete samples exposed to liquids was compared with the strength of concrete samples hardened in air.

Compressive strength of concrete was determined on testing samples measuring 70×70×70 mm by a PGM-1000MG4 hydraulic press.

The thermal conductivity coefficient of concrete was estimated using an ITP-MG4 device on samples measuring 100×100×10 mm.

Physical and mechanical tests of concrete were conducted on seven samples from each series. The range of test results was 4.2 – 5.8%.

To determine the phase composition of the materials, a modernized DRON-3M diffractometer with a BSV-24 X-ray tube with CuK α-radiation was used. The microstructure of the concrete was studied using a JSM-649OLV scanning electron microscope.

Porous aggregate is the basis of lightweight concrete. The fractional composition and porosity of the aggregate determine the density, thermal conductivity, and strength of lightweight concrete. Using computer modeling of the structure of large-pore geopolymer concrete, the fraction of granulated aggregate was adopted as 10 – 12 mm [32]. Hexagonal packing of aggregate particles with minimal separation of granules represents a stable framework.

The binding matrix holds the aggregate granules together at the contact points and partially fills the intergranular space (Figure 1). To obtain an aggregate of a given size, granules with a diameter of 8 – 10 mm and an average density of 970 kg/m^3 were molded from a liquid glass mixture.

Granules were porousized by thermal swelling. The effect of processing temperature on the composition, structure, and properties of granules was studied (Figure 2, Tables 2 and 3).

Temperatures of 150, 250, and 350°C with isothermal exposure for 60 minutes were selected for firing pellets. The formation of granules of a regular spherical shape was achieved as a result of swelling.

At the same time, the temperature of 150°C made it possible to achieve the optimal swelling coefficient of the granules – 1.20. With a subsequent increase in temperature, the diameter of the granules remained virtually unchanged (Table 2).

Firing granules at a temperature of 150°C ensures the greatest porosity.

The compressive strength and water resistance of granules are very sensitive to the firing temperature (Table 3). An increase in the firing temperature from 150 to 250 and 350°C is accompanied by an increase in the compressive strength of the granules by 1.7 and 1.5 times, respectively, and an increase in the water resistance of the granules by 3.0 and 3.5 times, respectively.

The increased compressive strength and water resistance of granules fired at temperatures of 250 and 350°C are due to the presence of crystalline compounds.

During heat treatment of a liquid glass mixture with the participation of anorthite and aluminosilicate amorphous phases, calcium and sodium hydroalumosilicates are formed, mainly hydrogelenite C_2ASH_8 and hydrosodalite NAS_2H_2 (Table 3).

The hardening of the material and an increase in its water resistance are achieved as a result of an increase in the proportion of crystalline compounds with increasing temperature.

To bind the porous aggregate in the concrete mixture, a binder with a similar composition to the granules is used. On the one hand, genetic kinship ensures reliable bonding of the concrete components and helps to increase the compressive strength of the material. On the other hand, liquid glass, having high adhesion to the porous aggregate, gives the concrete matrix a pronounced binding capacity. Thirdly, the related composition of raw mixes for the aggregate and binder of geopolymer concrete will allow organizing integrated production and reducing the firing temperature of granules to 150 – 200°C.

The low-temperature firing method makes it possible to ensure the strength of the granules is sufficient to preserve their integrity during further processing. Further firing of geopolymer concrete at a temperature of 350°C will make it possible to ensure the hardening of the binder and the hardening of the porous aggregate.

In the studied molding mixture, the ratio of the aggregate and binder volumes equal to 9:1 ensured the distribution of the binder matrix around the granules and partial placement in the intergranular space. To prepare the molding mixture, liquid glass was mixed with fly ash and an aluminosilicate microsphere.

The resulting suspension was mixed with porous granules, evenly distributing the binder between the aggregate. The flowability of the molding mixture was characterized by 2 – 3 cm of slump of the Abrams cone. Concrete curing mode: 1 hour – preliminary curing, 2 hours – heating to a temperature of 350°C; 2 hours – isothermal holding, 1 hour – cooling. The choice of the maximum temperature of concrete processing is made taking into account the thermal transformations during firing of the granulated liquid glass mixture (Table 3).

The results of tests of large-pore concrete are presented in Table 4.

The compressive strength of the structure of large-pore concrete is ensured by reliable adhesion of the aggregate to the binder in the interfacial transition zones (Figure 3).

The operational resistance of geopolymer concrete to the impact of water, magnesium sulfate, and sodium sulfate solutions was studied.

Concrete samples were kept in liquid media for 24 months, and visual studies were carried out (Figure 4). The concrete resistance coefficient was determined after 3, 6, 12, and 24 months (Table 5).

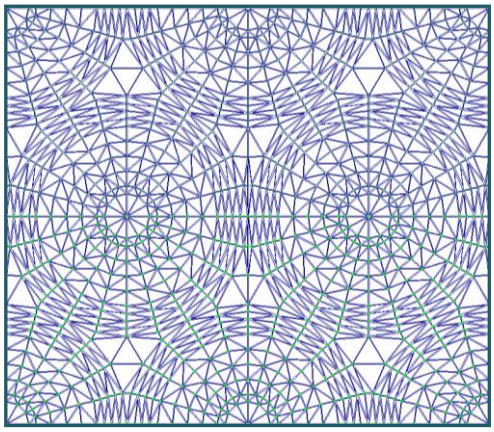


Figure 1 – Model of the structure of large-pore concrete

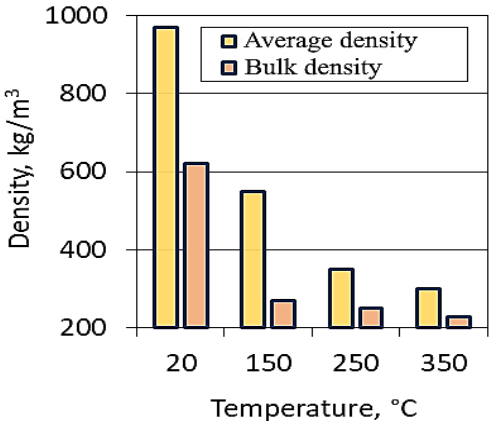
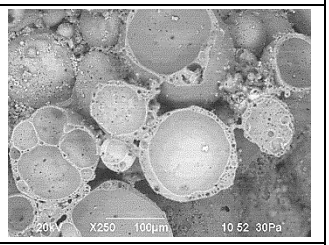
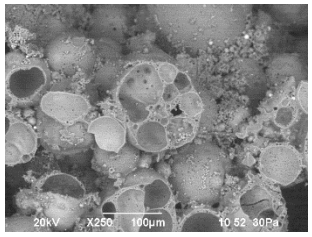
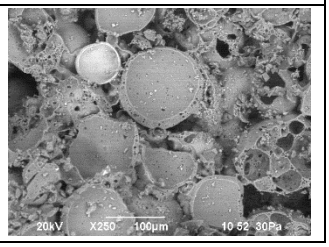


Figure 2 – Effect of processing temperature on granule density

Table 2 – Effect of firing temperature on granule structure

Firing temperature, °C	Swelling coefficient	Porosity, %	Granule structure mm	Microstructure
150	1.20	73.2		
250	1.20	76.0		
350	1.20	78.1		

Discussion of results

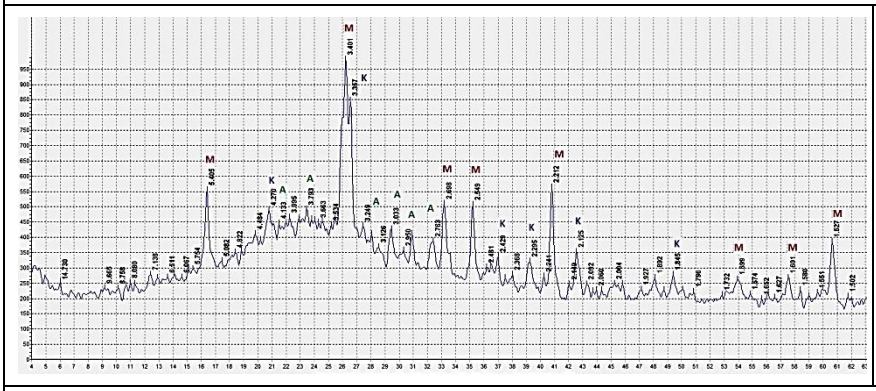
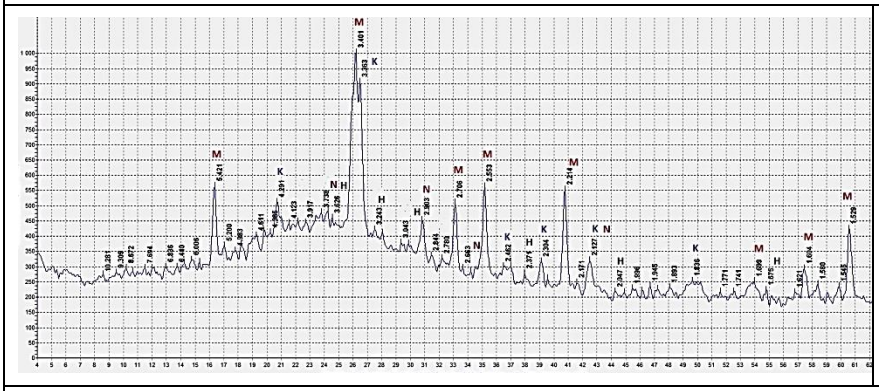
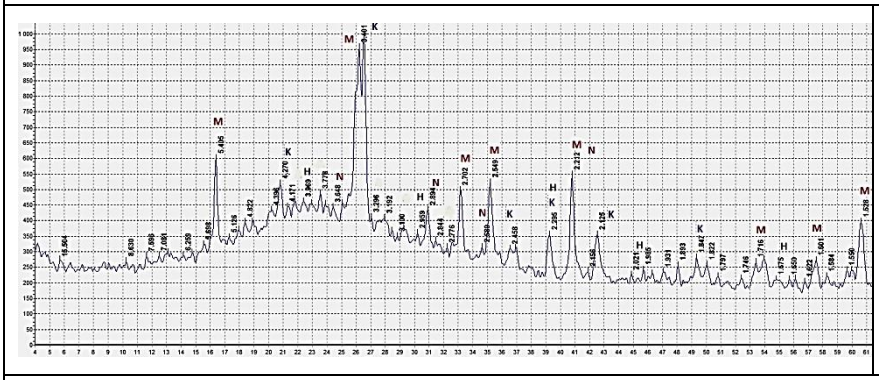
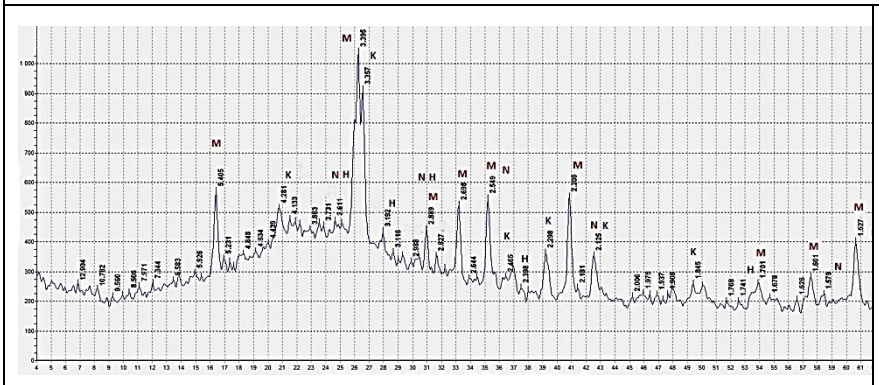
The concrete samples that were in water did not show any external signs of change (Figure 4).

The decrease in concrete strength should be associated with a decrease in the proportion of the amorphous component, as indicated by the decrease in the spectrum against the background of the XRD pattern in the range of angles of 16 – 38 degrees.

Concrete samples were observed to transform a magnesium sulfate solution (3% concentration) starting from 2 months.

The structure and components of the concrete retained their stability. At the same time, white amorphous clusters of magnesium hydroxide appeared in the intergranular space, which increased in size and became denser by 12 months (Figure 4).

Table 3 – Effect of firing temperature on the granules' composition and properties

XRD pattern *A – anorthite, K – quartz, M – mullite, H – hydrogelenite, N – hydrosodalite*	Compressive strength, MPa	Water resistance coefficient
Unfired		
	No determined	
150°C		
	1.9	0.25
250°C		
	3.3	0.75
350°C		
	2.9	0.87
Intensity, pulse/s 2Θ, degree		

General appearance | **Nature of destruction under compression by a press** | **Microstructure (red line – interfacial transition zone)**

Figure 3 – Structure of large-pore geopolymer concrete

Table 4 – Properties of large-pore geopolymer concrete

Properties	Values
Average density, kg/m^3	480
Compressive strength, MPa	4.7
Water absorption, %	31.0
Water resistance coefficient	0.87
Thermal conductivity coefficient, W/(m·°C)	0.095

The samples' state was stable from 12 to 24 months of exposure to a magnesium sulfate solution. The intensity of hydrate reflections changed in the concrete diffraction pattern (Figure 4): hydrosodalite reflections increased (d/n = 3.678; 2.671; 2.106 Å), and hydrogelenite reflections decreased (d/n = 3.576; 2.37; 1.734 Å).

The presence of geopolymer concrete in a sodium sulfate solution (concentration 5%) is accompanied by significant transformations of the composition and structure. After 2 months of exposure to an aggressive environment, thinning and destruction of the binder shells around the granules was observed.

This phenomenon is the result of the leaching of hydrate compounds from the geopolymer binder. This is confirmed by the data of diffractometric analysis: the «elevation» in the spectrum in the range of 16 – 38 degrees decreases.

Over the time of exposure of concrete to the sodium sulfate solution, gel-like masses appeared in the intergranular space and on the surface of the aggregate, released from the aggressive solution saturated with amorphous phases (Figure 4). The increased resistance of the granules compared to the binder matrix of concrete is due to the greater vulnerability of the matrix to external influences and the quantitative difference in the composition (Table 5).

For the economic assessment of large-pore geopolymer concrete, calculations of material and energy costs for the production of 1 m^3 of concrete were carried out.

For comparison, the indicators of cement expanded clay concrete of a similar structure, characterized by a thermal conductivity coefficient of 0.155 W/(m·°C), were used. The costs of the components of the molding mix of geopolymer concrete, according to preliminary calculations, are 84.5 U.S. dollars/m^3, which is 4.9 U.S. dollars/m^3 less than for cement expanded clay concrete.

The estimated energy costs for obtaining geopolymer concrete are 2.2 U.S. dollars/m^3, which is 1.4 times higher than the same indicator for cement expanded clay concrete.

This is due to the proposed mode of heat treatment of geopolymer concrete. Total costs of materials and energy for geopolymer concrete are 86.7 U.S. dollars/m^3, which is 4.3 U.S. dollars/m^3 less than for expanded clay concrete.

Large-pore geopolymer concrete is effective as thermal insulation. For the thermal resistance of the enclosing structure equal to 3.279 (m^2·°C)/W, the required thickness of the thermal insulation layer is: made of geopolymer concrete, a = [3.279 (m^2·°C)/W]·[0.095 W/(m·°C)] = 0.311 m; made of cement expanded clay concrete, a = [3.279 (m^2·°C)/W]·[0.155 W/(m·°C)] = 0.508 m.

The use of porous geopolymer concrete allows for a 1.63 – fold reduction in the consumption of materials for thermal insulation of wall structures.

The prospects for the implementation of the developed geopolymer porous concretes lie in their ability to give impetus to the development of small businesses in various regions [33].

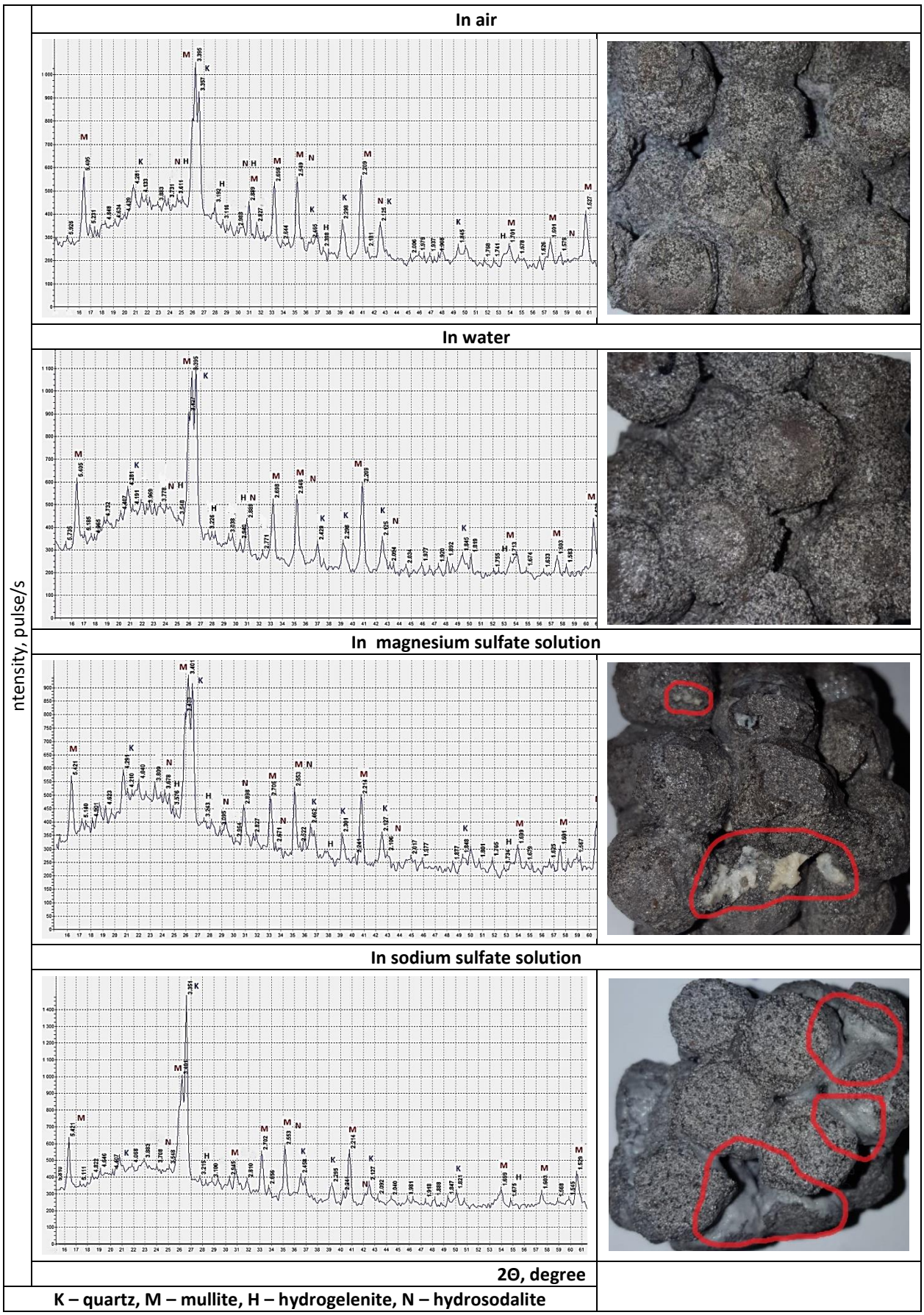


Figure 4 – XRD patterns (1) and appearance (2) of geopolymer concrete after 24 months of exposure to various environments

Table 5 – Resistance of geopolymer concrete to aggressive environments

Duration of the test, months	Resistance coefficient of geopolymer concrete		
	in water	*in magnesium sulfate solution (concentration 3%)*	*in sodium sulfate solution (Concentration 5%)*
3	0.82	0.76	0.52
6	0.78	0.73	0.48
12	0.76	0.70	0.45
24	0.75	0.69	0.40

Conclusions

Large-pore concrete has been developed, in which the binder and aggregate are formed as a result of geopolymerization processes.

The following main results were obtained.

Liquid-glass activation of thermal energy waste in combination with thermal treatment ensures the formation of a water-resistant composition and a stable porous structure of geopolymer concrete.

The use of raw mixes of related composition for the synthesis of porous aggregate and binder allows integrating technological processes, ensuring reliable adhesion of the components of geopolymer concrete.

The results of studies of phase transformations of geopolymer material under the influence of water and salt solutions indicate the prospects for further improvement of the technology of porous geopolymer concrete and the expansion of its scope of application.

Conflicts of interest. The author states that he has no conflicts of interest to disclose.

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Геополимерлі кеуекті бетон: қалыптастыру және пайдалану сипаттамалары

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Сараптамадан өтті: *4 наурыз 2026*
Қабылданды: *11 наурыз 2026*

ТҮЙІНДЕМЕ

Мақалада геополимерлік технологияны әзірлеу және кеуекті толтырғыш негізінде жеңіл бетонның сипаттамаларын зерттеу нәтижелері ұсынылған. Зерттеудің мақсаты – кеуекті геополимерлік бетонды қалыптастыру және пайдалану сынақтары процесінде құрамы мен құрылымының өзгерістерін анықтау. Кеуекті толтырғыш пен байланыстырушы зат ұқсас құрамдағы қалыптау қоспаларынан синтезделген, олардың құрамында сұйық натрий шынысы мен жылу электр станцияларынан алынған ұсақ дисперсті қалдықтар (ұшпа күл мен алюмосиликатты микросфера) бар. Механикалық жүктемеге және судың әсеріне қанағаттанарлық төзімділігі бар кеуекті құрылымды қалыптастыруды қамтамасыз ететін бетонды қатайтудың жылу режимі ұсынылды. Геополимерлік материалдың термиялық синтезі кезінде жүретін фазалық түрленулер, бетонға суға және магний мен натрий сульфатының ерітінділеріне ұзақ уақыт әсер ету кезіндегі өзгерістер зерттелді. Керамзит негізіндегі бетонмен салыстырғанда кеуектелген геополимерлік бетонның артықшылықтарын растайтын алдын ала экономикалық есептеулер жүргізілді. Әзірленген кеуекті геополимерлік бетондар энергия үнемдейтін қабырға бұйымдарын өндіруге арналған.

Түйін сөздер: Геополимерлеу, сұйық шыны, ірі кеуекті бетон, күл-тасу, тұз агрессиясы.

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Геополимерный пористый бетон: формирование и эксплуатационные характеристики

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АННОТАЦИЯ

В статье представлены результаты разработки геополимерной технологии и исследования характеристик легкого бетона на основе пористого заполнителя. Цель исследования – выявление преобразований состава и структуры в процессе формования и эксплуатационных испытаний пористого геополимерного бетона. Пористый заполнитель и вяжущее синтезированы из формовочных смесей родственного состава, содержащих жидкое натриевое стекло и мелкодисперсные отходы тепловых электростанций (зола-уноса и алюмосиликатная микросфера). Предложен тепловой режим отверждения бетона, обеспечивающий формирование пористой структуры, которая имеет удовлетворительную стойкость к механической нагрузке и воздействию воды. Исследованы фазовые превращения при термическом синтезе геополимерного материала, при продолжительном воздействии на бетон воды и растворов сульфата магния и натрия. Выполнены предварительные экономические расчеты, свидетельствующие о преимуществах поризованного геополимерного бетона по сравнению с цементным бетоном на основе керамзита. Разработанные геополимерные поризованные бетоны предназначены для энергоэффективных стеновых изделий.

Ключевые слова: Геополимеризация, жидкое стекло, крупнопористый бетон, зола-уноса, солевая агрессия.

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