Properties of Perlite-Based Geopolymer as a Thermal Insulation Material for Building Efficiency

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Abstract. Globally, the key issues related to technology and materials are the reasonable consumption of exhaustible resources, increasing technological efficiency, reducing waste, and sustainable production. The construction industry is responsible for huge carbon dioxide emissions and other harmful waste in this context. Moreover, it requires about 16 percent of the world's annual energy use for the production of cement-based products. Experts estimate that without effective changes, the negative impact on the environment and consumption will increase to 25% by 2050. This paper presents a geopolymer based on expanded perlite up to 85% that can be used as a modern lightweight thermal-insulation construction material. The results showed that the density of the samples varied from 330 kg/m3 to 510 kg/m3, the bending strength was from 1 MPa to 2 MPa, the compressive strength was from 13.5 MPa to 21 MPa, the thermal conductivity was from 0.09 W/m K to 0.130 W/m K, the water absorption coefficient was from 77% to 137%, and the total porosity of the material was from 60% to 65%. The results meet the requirements for lightweight building materials for wall construction regarding the leading indicators. Still, high water absorption significantly decreases strength and thermal conductivity after 100 h of the aging process. To reduce the water absorption of the perlite-based geopolymer, research is planned to apply a hydrophobic coating based on metakaolin.

Keywords: Expanded Perlite · Mechanical Properties · Thermal Conductivity · Lightweight Masonry Block · Perlite-Based Geopolymers

1 Introduction

The state of energy production and consumption in Ukraine has always determined its political situation and economic growth. Today, energy independence is a matter of national security and sustainable economic development. Due to limited energy resources, Ukraine imports about 50% of its total energy needs.

The Ukrainian government has taken certain steps in the last decade to reduce energy dependence and is striving to increase the share of renewable and alternative energy.

F. J. G. Silva et al. (Eds.): DSMIE 2025, LNME, pp. 76–87, 2025.
https://doi.org/10.1007/978-3-031-96413-8_8

Another effective method is to reduce the energy consumption ratio. In recent years, there has been a growing interest in energy conservation, as energy production is mainly achieved by burning fossil fuels, which will run out shortly. Today, the world's total primary energy consumption has reached approximately 85% from fossil fuels such as coal, oil, and natural gas [1, 2]. Approximately 50% of this consumption is spent directly on buildings. The EU is trying to abandon gas and oil as energy sources that pose both environmental and economic, military, and political risks. Thus, reducing energy consumption, especially in buildings, is crucial, as it will positively impact economic growth in the short and long term. Ukraine consumed 2.4 times more energy than the global average and 3.1 times more than the European Union. Since modern civilization cannot completely abandon energy consumption, the only way out of this situation is for it to rationally consume based on using renewable energy sources, energy-saving energy sources, energy saving, and the introduction of energy-efficient technologies.

As for materials, approximately 10 billion tons of structural materials are produced annually globally. This volume of production is responsible for 16% of global energy consumption and carbon emissions, with cement production alone accounting for almost 5%. So, summarizing the above, developing alternative thermal insulation construction materials is a relevant and essential task [3–5].

2 Literature Review

Many studies have been published aimed at producing heat-insulating materials from expanded perlite with low thermal conductivity. In their scientific work, Uller et al. experimentally investigated the production of thermal insulation panels based on expanded perlite with the lowest thermal conductivity at different cement-based binder contents. The authors found that the thermal conductivity values of thermal insulation panels decrease depending on the decrease in the binder ratio in the mixture. However, the reduction of the binder had a negative impact on the strength of the panels [6, 8]. In work [7], cementless pastes and mortar were produced based on alkaline activation using sodium hydroxide and sodium silicate of raw perlite with a hydrogen peroxide blowing agent. Articles [8, 9] represented the results of studies of geopolymers with the addition of expanded perlite, but the compressive strength was insignificant. The article presents the results of a study of the effect on thermal conductivity and compressive strength of geopolymers based on metakaolin with fillers in the form of swollen perlite and cellulose fibers. The strength was found not to exceed 6 MPa, and the thermal conductivity is in the region of 0.10 W/m [10]. In early works, perlite was considered a source of aluminum silicates in the form of a filler or precursor. Still, according to research results, it was considered an inefficient raw material with low mechanical properties in the final products [11–15]. For instance, in the study by Vance et al. [14], the results of the reactivity of perlite of different fractions with NaOH solution were presented. The geopolymerization temperature of the composite was determined. However, the composition based on perlite alone did not provide sufficient strength, and only the addition of fly ash to the composition increased the compressive strength. It was investigated that perlite waste in interaction with alkaline solutions (10 M NaOH) formed crystalline zeolite 4A and other crystalline phases. However, the compressive strength of the obtained geopolymers was low. After the addition of perlite up to 22.5%, fly ash up to 40%, and calcined kaolin clay 10% by weight, it was possible to increase the mechanical properties to acceptable values [16–19] It was revealed [20, 21] that the formation of a zeolite phase and a heterogeneous structure in perlite geopolymers causes a decrease in strength. The maximum ratio of perlite to geopolymer at which the mechanical properties are reasonable for the production of materials is in the range of 70–80%.

Papadopoulos [22] emphasizes that despite a significant amount of research on materials based on expanded perlite in the last decade, the thermal properties of such composites have not improved significantly, except for fire resistance. The study of pressure-sintered composites based on expanded perlite is considered by the authors in [23]. In the study by Kornienko et al. (2023), expanded perlite and vermiculite were used as lightweight fillers in geopolymers, the authors found a slight effect of fillers on strength properties, but the density and thermal conductivity of materials decreased significantly. Such fillers are characterized by good adhesion to the geopolymer matrix [24]. The filling of the geopolymer based on fly ash with 10% expanded perlite led to an increase in plasticity but a decrease in compressive strength by up to 40% [25].

Based on the above, the main goal of this work was to develop a geopolymer for structural purposes with a high degree of filling up to 85% by weight of expanded perlite as a filler, which provides a low coefficient of thermal conductivity. According to the analysis of literary sources, the authors failed to obtain sufficient compressive strength with a perlite filling content above 50% by weight without the use of metakaolin as a binder. Accordingly, the developed materials as an alternative to materials based on cement technologies should meet the general requirements for structural and thermal insulation building materials.

3 Research Methodology

The following materials were used to prepare the compositions: expanded perlite from the Fogosh deposit, sieved on laboratory sieves 1.8 to 2.2 mm, liquid sodium silicate glass as a binder, and plasticizer Sika Mix Plus (Switzerland).

The components were added in the following sequence: first, the plasticizer was mixed with perlite, then the binder was added. To form the compositions, metal molds with dimensions of 50 × 50 × 50 mm were used, which were pre-lubricated with graphite grease, then the compositions in the mold were pressed with a force of 980 N and sintered in an oven at 200 °C for 1 h.

Five compositions of the composite were prepared, the general view of which is shown in Fig. 1: No. 1 - (5 mass fraction of perlite +1 mass fraction of liquid glass); No. 2 - (5 mass fraction of perlite +2 mass fraction of liquid glass); No. 3 - (5 mass fraction of perlite +3 mass fraction of liquid glass); No. 4 - (5 mass fraction of perlite +4 mass fraction of liquid glass); No. 5 - (5 mass fraction of perlite +5 mass fraction of liquid glass) and 0.1 mass fraction plasticizer was added to each composition. The ratio of the components was determined based on the results of mathematical modeling using MATLAB tools.

The water absorption of the samples (Wi) was determined as the average of the water absorption of all samples, calculated to an accuracy of 1%. The samples were placed in

Fig. 1. General view of samples.

a bath on a mesh stand and loaded with a weight. Thermal conductivity measurements were performed using a plating apparatus HZM 446 Lambda Small (NEZTSCH, Selb, Germany). The temperature stabilization accuracy was ±0.2 °C.

Porosity measurements were performed by using a Quantachrome Instruments Poremaster mercury porosimeter. The study was conducted for composites No. 1, No. 3, and No. 5, each subjected to high- and low-pressure tests. The maximum value during the low-pressure test is about 50 PSI; during the high-pressure test, this value is about 35.000 PSI, due to the difference in the volume of mercury introduced into the sample. During a high-pressure test, mercury may have penetrated less accessible pores; therefore, the amount of mercury injected is greater. Mercury porosimeter can measure pores with a size of approximately 250–0.003 μm.

The compressive strength test was carried out on the MATEST 3000 km device. The linear rate of force increase was 1.25 kN per second. All tests were carried out after 28 days of sample curing. All data are the average of three to six repetitions.

The elemental and oxide composition was measured using two methods (for comparative purposes)—the first method used loosely packed expanded perlite powder for measurements. In the second method, measurements were performed on compressed material by using The S2 PUMA Series 2 XY Autochanger X-ray fluorescence spectrometer (XRF) (Bruker, Billerica, Volumeachusetts, United States To prepare the sample for measurement, 6 g of expanded perlite was weighed, to which 1.5 g of wax (Licowax® C micro powder, PD Instruments, Toszek, Poland) was added.

The microstructure observations of expanded perlite were performed using a JEOL JSM-820 scanning electron microscope (IXR Inc., Austin, TX, USA). Before observation, the samples were prepared by sputtering with a gold layer in a JOEL DII-29030SCTR vacuum coater (IXR Inc., Austin, TX, USA).

The perlite particle size distribution was analyzed using a laser particle analyzer, Anton Paar GmbH (Graz, Austria), which uses the light diffraction technique. The measurement was performed in wet mode, which required the preparation of a metakaolin sample and its introduction into the device, where the light scattering analysis was then performed. The study established statistical values of grain size based on six measurements.

4 Results and Discussion

4.1 Characterization of Raw Material

The chemical composition of the tested precursors was determined by the XRF method. Perlite is considered an important raw material for the production of geopolymers; however, the reactivity depends on the chemical composition. The results of the chemical composition study are given in Table 1.

Table 1. Perlite chemical element compositions (X-ray fluorescence).

Element [Volume%]											
	Si	Al	K	Fe	Na	Ca	Ti	Mg	Cl	Mn	Rb
Expanded perlite	65.73	11.95	10.65	3.96	3.56	3.08	0.23	0.22	0.18	0.15	0.07

The perlite particles had an irregular spherical morphology with a rough and porous texture, which is an advantage for achieving a successful geopolymerization process (Fig. 2).

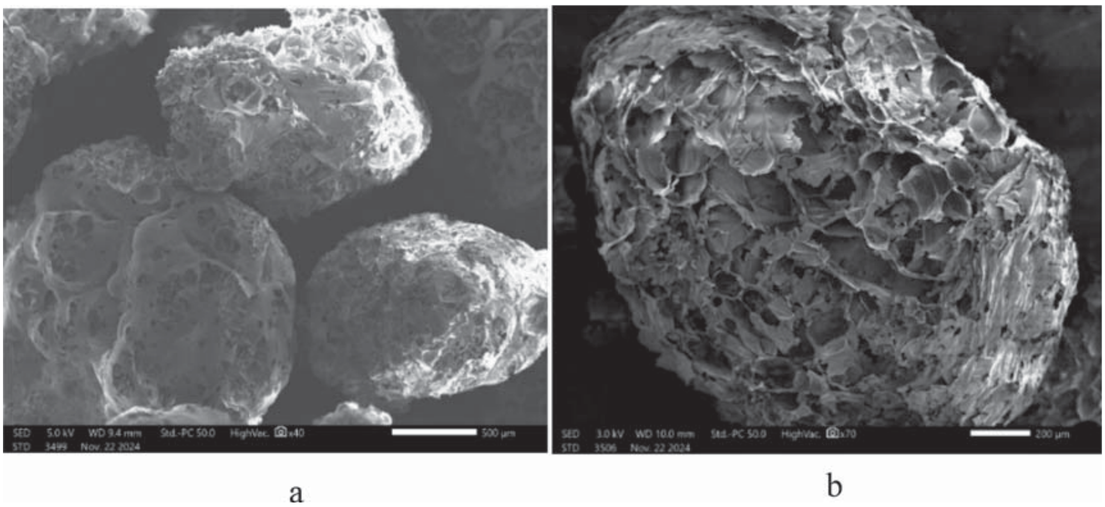

Fig. 2. SEM micrographs of expanded perlite morphology: a) ×40; b) ×70.

This improves the rheological properties of the mixture, increasing its ease of placement. In addition, it reduces the need for liquids and has a beneficial effect on the mechanical properties of geopolymers [26]. The size of the perlite particles (Fig. 3) after sieving ranged from 10 to 2000 μm, where 90% of the particles are larger than 700 μm and the D_{50} distribution width is 650 μm. The larger particle size results in a lower

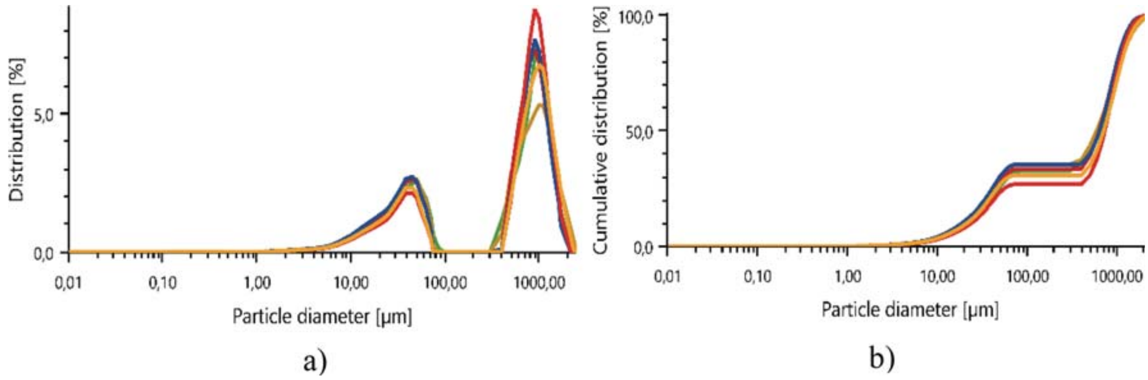

Fig. 3. Results of particle size analysis: (a) particle size distribution histogram; (b) cumulative particle size distribution curves.

specific density and greater porosity, which positively affects the thermal conductivity coefficient.

Furthermore, the porosity is the biggest at the biggest particle size and the voids can be better filled within big particles, which can lead to denser and stronger geopolymer products. Figure 4 shows the diffractogram recorder for expanded perlite. The results of X-ray studies showed that in the analyzed perlite, it was possible to detect the presence of impurities in the form of the SiO_2 crystalline phase. This phase does not participate directly in the polymerization process. The recorded XRD curve indicates the presence of the amorphous phase in the tested perlite (a very large hump). Amorphous phases play an important role in the polymerization process [25–28, 29] (Table 2).

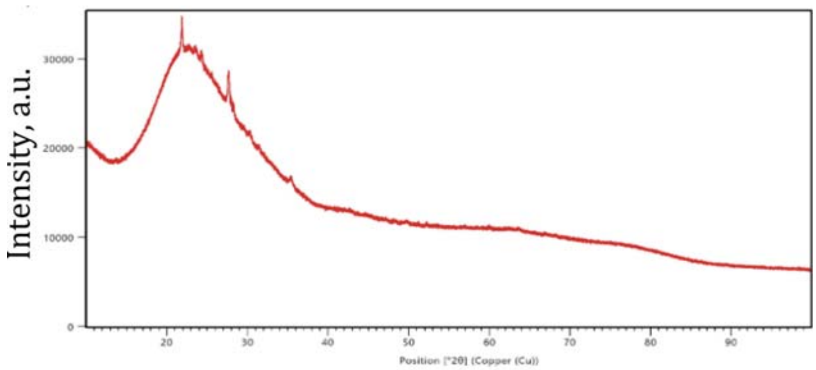

Fig. 4. Diffractogram for perlite

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Table 2. Particle size distribution in expanded perlite.

Name	D_{10}(μm)	D_{50}(μm)	D_{90}(μm)	Mean size(μm)	Span	Color
Perlite 1	22.183	646.033	1272.342	651.459	1.935	
Perlite 2	19.650	589.593	1372.794	652.600	2.295	
Perlite 3	19.967	629.843	1210.398	627.373	1.890	
Perlite 4	18.586	635.847	1192.769	615.257	1.847	
Perlite 5	23.525	730.627	1265.677	712.669	1.700	
Perlite 6	21.011	708.141	1363.656	712.337	1.896	

4.2 Water Absorption Test

The test for water absorption of a perlite-based thermal insulation composite consists in measuring the volume of water absorbed by a dry material sample completely immersed in water for a given time, presented in Table 3.

Table 3. Water absorption and density thermal insulation composite.

No. of composition	The ratio (perlite + liquid glass)	Water absorption, Wi, %	Density, kg/m^3
1	5:1	136.2	330
2	5:2	120.4	360
3	5:3	98.8	410
4	5:4	84.7	459
5	5:5	76.5	510

It was established that the minimum value of water absorption (Wi = 76.5%) with a density (510 kg/m^3) is obtained for composition No. 5, which has a ratio of 5:5 (perlite + liquid glass) and was formed at a temperature of 400 °C. The highest value of water absorption (Wi = 136.2%) with a density (of 330 kg/m^3) is observed in composition No. 1, which has a ratio of 5:1 (perlite + liquid glass) According to the dependence, water absorption decreases with an increase in the amount of liquid glass, which can be explained as a consequence of a decrease in the number of open and closed pores, as well as a reduction in the area of perlite inclusions due to the coating of the liquid glass matrix, which in turn blocks the contact of water with the adsorbing surface of perlite, which is a water-absorbing component in the composition. According to the results, the material requires a surface coating with a hydrophobic material to meet the operational requirements in real conditions.

Table 4. The results of the porosity measurements.

Sample	Total interparticle porosity [%]	Total intraparticle porosity [%]	Total porosity [%]	Theoretical porosity [%]
1 Low	65.14	0.000	65.14	79.31
1 High	0.011	0.0156	0.0266	77.68
3 Low	64.4	0.000	64.4	74.63
3 High	0.005	0.025	0.030	76.25
5 Low	61.55	0.000/-	61.55	70.6
5 High	0.027	0.084	0.111	72.7

4.3 Porosity Measurement

The summation of the two indicators provides information on the total porosity of the materials under test. Moreover, the theoretical porosity of the material is calculated based on the measurement. The results of the porosity measurements are presented in Table 4.

Testing under high pressure provides information on intraparticle porosity. The value depends on material characteristics, especially pore characteristics. In the case of closed pores, information on porosity may be missing. The ability to conduct tests under high- and low-pressure conditions provides more objective information.

Based on the results obtained, it was found that the theoretical porosity of perlite-based geopolymer, depending on the content of the perlite, is about 79% for composition No. 1, about 75% for composition No. 3, and about 71% for composition No. 5.

4.4 Mechanical Properties

Compressive strength test results are shown in Fig. 5. The highest strength value is 23 MPa for the sample of thermoperlite No. 5 with a component ratio of (5:5). According to the obtained dependence, the strength of the composite increases almost linearly with an increase in the binder content up to composition No. 3, and then no significant increase in strength is observed.

The obtained strength values make it possible to use this material in construction since the widely used ceramic brick of the M150 brand has a compressive strength of 15 MPa. Compared to other alternative materials, such as those used by the authors of [24], the strength of the geopolymer filled with perlite was only 2.3 MPa, and that filled with vermiculite was 3.75 MPa. The obtained strength values are higher than the average values obtained by other authors [6, 11, 23]. Mechanical properties correlate with the porosity of the material and its density.

Thus, it is highly probable that it results from water saturation and disruption of the formed relationships between the binder and filler, by comparing the obtained compressive strength results with those of [13, 14]. We can state that for the created geopolymers, even at a specific density of 300 kg/m^3, the compressive strength meets the standard's requirements for such materials. A low thermal conductivity coefficient was obtained, which is one of the most essential properties. The strength results from forming good

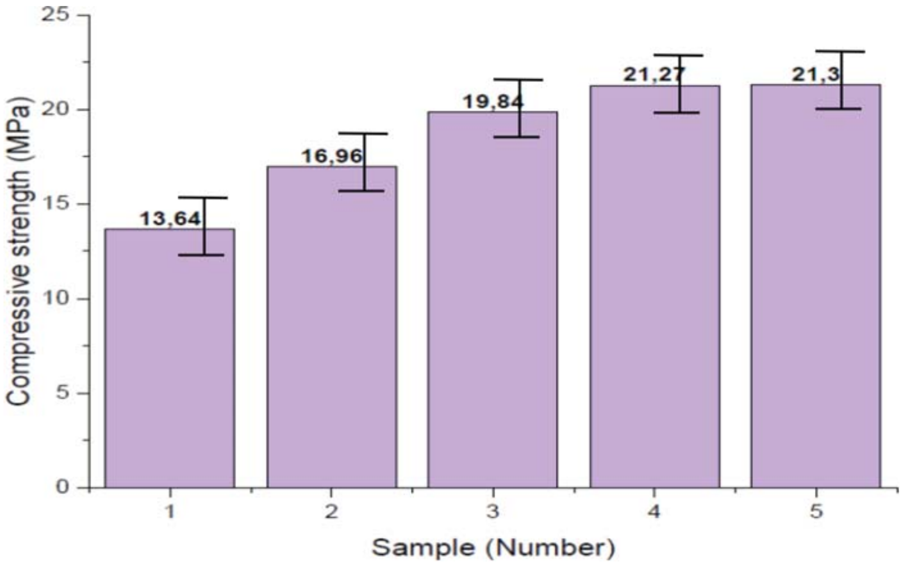

Fig. 5. The results of compressive strength tests (after 28 days of curing).

chemical bonds between the particles due to temperature treatment under load. Similar materials based on metakaolin studied in [28] have higher strength values but are inferior in terms of thermal conductivity, and metakaolin is, on average, 7 times more expensive than perlite.

4.5 Durability and Thermal Conductivity Test

The samples were moistened to the humidity values of the operating conditions hermetically sealed in special plastic bags and exposed to different temperatures. Thus, at the first stage of the test, the samples were subjected to freezing at a temperature of −22 °C. Then, the samples were thawed at a temperature of +20 °C, and then, in the third stage, they were heated to a temperature of +60 °C. After every tenth cycle, samples were taken to determine their thermal conductivity under standard conditions, the results of which are shown in Fig. 6, and changes in the appearance of the material were recorded.

According to the results of the visual inspection of the test samples after 100 cycles of climatic effects of freezing-thawing-heating, it was found that the appearance of the samples of the thermal insulation composition does not change - the change in the geometric dimensions of the samples is within the limits of permissible values, there is no change in the color and structure of the material, the general view of the composition is shown in Fig. 7.

The tests were performed following DSTU B V.2.7-182-2009. As a result, it was determined that the period of usage of perlite geopolymer for thermal insulation of buildings is at least 50 years. This indicator not only fully complies with the norms of DSTU B.2.6-31: 2006, but also exceeds it by 2 times.

Analyzing the study results, the specific density is in the range of 330–510 kg/m^3 with a total porosity of 60 to 65%, compressive strength from 13 to 20 MPa, and thermal conductivity from 0.09 to 0.13. W/(m K). It can be stated that the experimental materials meet the requirements of Ukrainian standards in terms of the leading indicators of mechanical characteristics, as they are not inferior to widespread Autoclaved Aerated

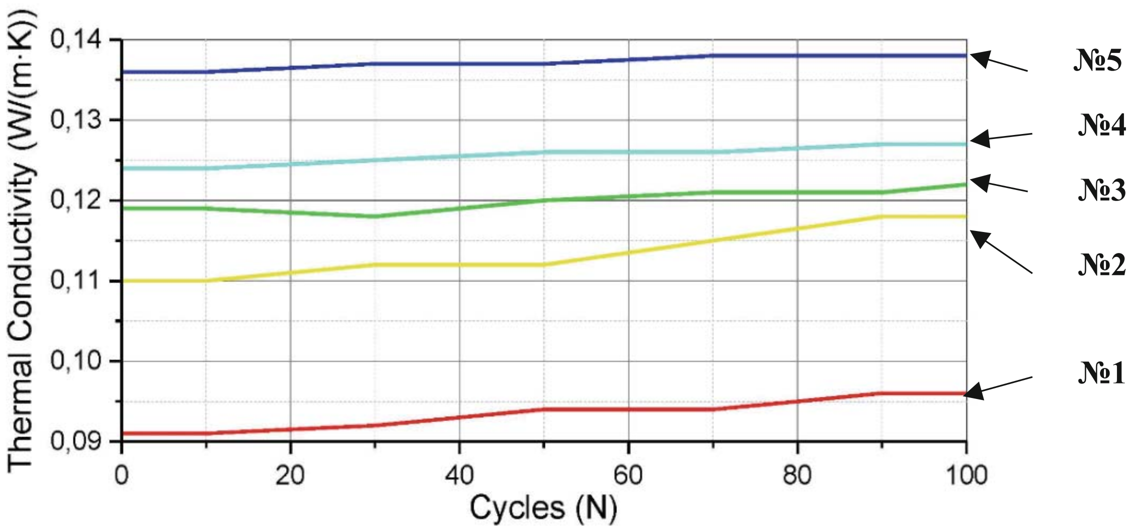

Fig. 6. Relation of thermal conductivity to the number of thermal cycles.

Concrete (AAC) and have significantly better thermal conductivity and specific density compared to bricks.

However, according to the results, significant drawbacks need to be addressed in future studies, such as the high-water absorption coefficient, which leads to a decrease in mechanical properties, as found during the wetting aging test. In addition, the sintering molding method requires additional energy consumption. Future research will focus on molding methods without additional sintering and reducing water absorption.

5 Conclusions

This paper presents the possibility of the development of lightweight masonry blocks based on expanded perlite. It has been shown that can produce geopolymer with content up to 85% expanded perlite, which was formed by treatment with pressure and temperature of 200 °C.

According to the results of the durability test, it was found that the phase of use of perlite-based geopolymers for thermal insulation of buildings is at least 50 years. After 100 thermal cycles of freezing and heating, the thermal conductivity of the material increased by an average of 10% for almost all compositions. It was found that the total porosity, depending on the composition, ranges from 65% to 60%, which correlates well with the results of determining the thermal conductivity, which is in the range of 0.09 to 0.13 W/(m K). The water absorption coefficient was from 77% to 137%, The compressive strength of the studied composites depends on the composition and ranges from 13 to 21 MPa, the bending strength was from 1 MPa to 2 MPa. It has been investigated that this material does not contain harmful components and is eco-friendly.

Accordingly, this material, based on the results obtained, has prospects as a lightweight construction building material. In further studies, it is necessary to find the methods for reducing water adsorption and investigate the impact strength and fire resistance.

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