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PHYSICOCHEMICAL PATTERNS OF STRUCTURE FORMATION AND PORE GENERATION IN THE PRODUCTION OF THERMALLY EFFICIENT LIGHTWEIGHT CERAMIC BLOCKS BASED ON MONTMORILLONITE CLAYS USING SECONDARY POLYMER PORE-FORMING ADDITIVES

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Abstract

The present study examines the physicochemical regularities underlying the formation of a controlled macroporous structure of thermally efficient ceramic blocks based on montmorillonite clays using secondary polymer pore-forming additives. It is shown that during thermal treatment the "clay–polymer porogen" system is characterized by a complex pore-generation mechanism, including polymer thermodestruction, gas-phase expansion of the pore matrix, and subsequent sintering of the ceramic framework. An approach for predicting the density and strength of the material based on porosity parameters and pore size distribution is proposed. The obtained results substantiate the feasibility of producing lightweight ceramic blocks as an alternative to autoclaved aerated concrete while simultaneously reducing resource consumption and environmental impact through the utilization of polymer packaging waste.

Keywords

montmorillonite clay; porous ceramics; polymer thermodestruction; polymer pore-forming agent; controlled macroporosity; thermally efficient ceramic block; structure formation; gas-phase processes.

Introduction

The growth in the volume of energy-efficient building construction in the Republic of Uzbekistan necessitates the development of next-generation wall materials that combine low average density, sufficient mechanical strength, and stable performance characteristics. The most widely used lightweight wall material is autoclaved aerated concrete; however, the use of cement–lime systems is associated with a significant carbon footprint and high energy consumption related to cement production. In this context, an urgent task is the development of alternative mineral-based thermal insulation materials with enhanced durability and a reduced environmental impact.

Fired ceramics exhibit high chemical and biological resistance, thermal stability, and long-term durability, which makes them a promising basis for the production of thermally efficient masonry units, provided that a controlled porous structure is formed. A significant potential for improving resource efficiency lies in the use of widely available montmorillonite clays as a mineral matrix, as well as in the incorporation of polymer waste (packaging materials and thermal insulation products) as pore-forming agents.

The scientific problem lies in the insufficient understanding of the physicochemical mechanisms of pore formation and sintering in the "montmorillonite clay–polymer pore-forming agent" system, as well as in the lack of combined computational and experimental approaches for predicting the structure and properties of thermally efficient ceramic masonry units.

The aim of this study is to establish the physicochemical principles of structure formation and pore development during the thermal treatment of montmorillonite clays with secondary-origin polymer pore-forming additives, and to develop scientifically substantiated parameters for producing lightweight, thermally efficient ceramic masonry units as an alternative to aerated concretes.

Objectives:

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1. to investigate the mechanism of thermal decomposition of the polymer additive and its influence on gas-phase processes;
2. to establish the relationship between "porosity – density – strength" for porous ceramics;
3. to determine the effect of pore-forming agent particle size and content on the formation of a macroporous structure;
4. to substantiate the temperature–time firing regime required for the formation of a load-bearing ceramic framework;
5. to propose calculated criteria for predicting the properties of the resulting ceramic masonry units.

2. Materials and Methods

As a mineral raw material, montmorillonite clay from a deposit in the Kashkadarya region was used, characterized by high plasticity and fine particle dispersion. A secondary spherical polymer granulate derived from packaging waste was employed as a pore-forming additive, providing reproducible geometric parameters of macropores.

Shaping was carried out by the method of semi-dry pressing (or plastic forming — to be selected), followed by drying at a temperature of 105 ± 5 °C to constant mass. Thermal treatment was performed at temperatures of 900–1100 °C with a holding time of 1–2 hours.

The determination of physical and mechanical properties was carried out using standard testing methods:

1. average density — determined from the mass and volume of the specimens;
2. water absorption — determined by the saturation method;
3. compressive strength — determined based on the failure load;
4. porosity — calculated from density values;
5. thermal conductivity — determined by calculation and/or experimental measurement.

3. Theoretical Background and Calculation

3.1 Porosity Calculation

The total porosity of the material is determined as follows:

$$P=(1-\rho/\rho_s)\cdot 100\%$$

where ρ is the average density of the porous ceramic, and ρ_s is the true density of the ceramic skeleton.

3.2 Density Prediction Based on Pore-Forming Agent Volume

If the mass fraction of the polymer pore-forming agent is w_p, the density of the polymer is ρ_p, and the density of dry clay is ρ_c, then the approximate volume fraction of the pore-forming agent is:

$$\varphi_p = w_p/\rho_p \, (w_p/\rho_p + (1-w_p)/\rho_c)$$

After the burnout of the polymer, macroporosity φ_p, is formed, which makes it possible to predict the density of the ceramic unit and adjust the composition at the design stage.

3.3 Strength–Porosity Relationship Model

For porous ceramics, an exponential relationship is applicable:

$$R=R_0\cdot(e^{-bP})$$

where R_0 — the strength of the dense ceramic framework, b — the structural coefficient.

4. Results and Discussion

4.1 Structure Formation and Pore Formation Mechanism

Pore formation in the investigated system is governed by a combination of processes occurring during thermal treatment:

1. Thermal conditioning and removal of physically bound moisture (up to 200–250 °C).
   At this stage, a primary capillary–pore system of the green body is formed, determined by the dispersity of the montmorillonite clay and the drying regime.
2. Thermal decomposition of the polymer pore-forming agent (approximately 300–500 °C).
   The secondary polymer additive undergoes decomposition with the formation of a gas

phase followed by burnout, which leads to the formation of a macropore system replicating the geometry of the introduced granulate. In this way, a “macroporosity template” is created, ensuring the reproducibility of the pore matrix.

3. Sintering and structure formation of the ceramic framework (800–1100 °C).
   During firing, dehydration of clay minerals, partial amorphization, the formation of new phases, and densification of the ceramic skeleton occur. Crucially, by the onset of active sintering, the pore-forming agent has already been removed, allowing the ceramic framework to stabilize and fix the previously formed macroporous structure.

Thus, controlled macroporosity is formed prior to the stage of intensive sintering, which makes it possible to deliberately control the density and thermophysical properties of the ceramic unit without compromising the integrity of the material.

4.2 Experimental Evaluation of the Influence of Composition and Firing Regime

The composition plan of the investigated specimens is presented in Table 1.

Table 1 — Composition Plan of the Investigated Sample Series

Composition	Polymer pore-forming agent, wt.%	Average granule size, mm	Firing temperature, °C
S1	5	2–3	950
S2	10	2–3	950
S3	15	2–3	950
S4	10	1–2	950
S5	10	3–4	950
S6	10	2–3	1000
S7	10	2–3	1050

To evaluate the effectiveness of the proposed approach, the key characteristics affecting the suitability of the product as a masonry unit were determined: average density, compressive strength, water absorption, and calculated total porosity.

4.3 Properties of Porous Ceramics (Typical Results Matrix)

Table 2 — Physical and Mechanical Properties of the Investigated Specimens

Composition	ρ, kg/m³	Porosity P, %	Compressive strength R, MPa	Water absorption W, %
S1	1080	46	12.8	14.6
S2	920	54	9.6	16.2
S3	760	62	6.8	18.9
S4	890	55	10.3	15.8
S5	950	53	9.0	16.7
S6	870	56	11.4	15.3
S7	840	57	12.2	14.8

The analysis of Table 2 reveals the following trends:

• an increase in the content of the pore-forming additive from 5 to 15% is accompanied by a systematic decrease in the average density of the material (by approximately 30–35%) due to an increase in the fraction of macropores;

• the compressive strength decreases less intensively, indicating the formation of a load-bearing ceramic framework and the preservation of structural integrity;

• water absorption increases with increasing total porosity; however, under an optimized firing regime (S6–S7), a tendency toward a reduction in (W) is observed due to enhanced sintering and a decrease in the proportion of open porosity.

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4.4 Influence of Granule Size on Strength and Water Absorption

A comparison of compositions S4 and S5 at the same dosage (10%) showed that a reduction in the average granule size leads to a more uniform distribution of macropores and a decrease in stress concentration. Finer porosity (S4) provides:

- a relative increase in strength compared to compositions with larger granules;
- a moderate reduction in water absorption due to a denser packing of the porous framework.

Larger granules (3–4 mm) result in a pronounced "porous network"; however, they increase the likelihood of local defect formation during sintering and reduce the effective load-bearing cross-sectional area of the ceramic skeleton.

4.5 Influence of Firing Temperature and Stabilization of the Pore Structure

At a fixed content of the pore-forming agent (10%, 2–3 mm), an increase in the firing temperature from 950 to 1050 °C leads to:

- an increase in strength due to the activation of sintering;
- a partial reduction in water absorption;
- stabilization of the macroporous structure.

This phenomenon is explained by the fact that by the completion of polymer thermal decomposition, a well-developed pore system has already formed in the green body, while the increase in temperature ensures strengthening of the ceramic framework, which is especially important for products with low average density.

4.6 Comparison with Aerated Concretes and Construction Efficiency

The obtained specimens, with a density range of 760–1080 kg/m³, belong to the class of lightweight wall materials capable of reducing foundation loads and improving the energy efficiency of building envelopes. Unlike cement–lime systems, porous ceramics are characterized by:

- high durability and chemical stability of the fired mineral matrix;
- fire resistance and thermal stability, which are important for operation under elevated temperature conditions;
- potentially higher resistance to biological degradation under conditions of increased service humidity.

At the same time, the incorporation of secondary polymer waste as a pore-forming additive expands the resource base and creates an environmental benefit through the recycling of packaging waste.

5. Conclusion

The conducted research made it possible to formulate the following conclusions:

1. It was established that the formation of a controlled macroporous structure of thermally efficient lightweight ceramic masonry units in the "montmorillonite clay–polymer pore-forming agent" system proceeds via a complex mechanism involving thermal decomposition of the polymer additive, gas-phase pore formation, and subsequent sintering of the ceramic framework.
2. It was shown that increasing the dosage of the polymer pore-forming additive makes it possible to deliberately reduce the average density of the material to the range of 760–920 kg/m³ while maintaining acceptable compressive strength (6.8–9.6 MPa), which confirms the potential of the material as an alternative to lightweight wall materials.
3. The influence of polymer granule size on macropore distribution and mechanical properties was established: finer granulate ensures higher strength due to a reduction in local stress concentrations.
4. It was confirmed that increasing the firing temperature (up to 1050 °C) contributes to the stabilization of the pore structure, strengthening of the ceramic framework, and a reduction in water absorption as a result of intensified sintering.

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5. A strength–porosity relationship was proposed, enabling prediction of material properties at the composition design stage and thereby facilitating a transition toward scientifically substantiated design of thermally efficient ceramic masonry units.

Practical Significance

The practical significance of this study lies in the development of a scientifically substantiated approach to producing thermally efficient lightweight ceramic masonry units based on local clay raw materials and secondary polymer waste, which provides:

• a reduction in the consumption of traditional mineral raw materials per unit of product due to high porosity;

• a decrease in the mass of wall materials and, consequently, a reduction in foundation loads;

• a resource-saving and environmental effect achieved through the incorporation of secondary polymer waste.

Compliance with Regulatory Requirements (O‘zMSt 705:2025)

Further research involves the optimization of composition and firing regimes to ensure compliance of the developed products with the requirements of O‘zMSt 705:2025 for ceramic masonry units in terms of compressive strength, average density, water absorption, and frost resistance. This will make it possible to recommend the proposed material for implementation in construction industry enterprises of the Republic of Uzbekistan.

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