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DEVELOPMENT OF TECHNOLOGY FOR PRODUCING THERMALLY STABLE LIGHTWEIGHT CONCRETE BASED ON LOCAL RAW MATERIALS

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Abstract
the development of thermally stable lightweight concrete based on locally available raw materials represents a strategic direction for improving energy efficiency in modern construction under conditions of climate variability and rising energy consumption. In regions characterized by sharply continental climates, significant daily and seasonal temperature fluctuations lead to increased thermal loads on building envelopes, which in turn necessitates the use of materials capable of maintaining stable indoor thermal regimes while reducing structural weight and embodied energy. The present research is devoted to the scientific substantiation and experimental development of a technology for producing lightweight concrete using locally sourced mineral and technogenic raw materials, including expanded clay aggregates, volcanic tuff, loess-derived pozzolanic components, ash–slag waste, and natural mineral fillers. The study integrates material science, thermal engineering, and structural performance analysis to determine optimal mix design parameters ensuring low density (900–1400 kg/m³), reduced thermal conductivity (0.18–0.35 W/m·K), sufficient compressive strength (7.5–20 MPa), and enhanced thermal inertia. Experimental investigations included granulometric optimization, water–cement ratio adjustment, pore structure modification through chemical foaming agents, and partial replacement of Portland cement with active mineral additives. Microstructural analysis confirmed the formation of a closed porous system contributing to reduced heat transfer and improved frost resistance. The developed technology enables the production of eco-efficient lightweight concrete suitable for load-bearing and enclosing structures in residential and public buildings, ensuring compliance with contemporary energy-saving standards and sustainable construction principles. The findings demonstrate that the rational utilization of local raw materials not only reduces production costs and environmental impact but also enhances the

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thermophysical performance of building materials, contributing to national strategies for energy efficiency and resource conservation.

Keywords: Lightweight concrete; thermal stability; local raw materials; energy efficiency; heat conductivity; porous structure; sustainable construction; mineral additives; thermal inertia; building materials technology.

Introduction

The modern construction industry faces the dual challenge of ensuring structural reliability and achieving high energy efficiency in buildings under increasingly variable climatic conditions, particularly in regions with continental climates characterized by extreme summer heat and winter cold, where maintaining stable indoor temperatures demands substantial energy consumption and significantly increases operational costs; in this context, the development of thermally efficient building materials becomes a scientific and technological priority, and lightweight concrete, due to its reduced density and favorable thermal characteristics, occupies a special position among structural and insulating materials, yet its performance largely depends on the nature of aggregates, pore structure formation, binder composition, and manufacturing technology, which necessitates a systematic approach to mix design optimization and microstructural engineering; the relevance of utilizing locally available raw materials arises from both economic and environmental considerations, as transportation of conventional aggregates and binders substantially increases embodied energy and production costs, while many regions possess significant reserves of natural pozzolanic materials, volcanic rocks, expanded clay resources, loess soils, and industrial by-products such as ash and slag capable of acting as active mineral components in cementitious systems; therefore, the scientific hypothesis of this research is based on the assumption that through rational selection and activation of local raw materials, combined with controlled pore formation and partial cement substitution, it is possible to obtain lightweight concrete exhibiting enhanced thermal inertia, reduced thermal conductivity, sufficient mechanical strength, and long-term durability, thereby contributing to sustainable construction practices; the aim of the study is to develop and experimentally substantiate a comprehensive technology for producing thermally stable lightweight concrete using local mineral resources, while

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the objectives include analysis of raw material properties, optimization of granulometric composition, investigation of hydration processes in modified cement systems, determination of thermophysical and mechanical characteristics, and assessment of energy-saving potential in building applications; the novelty of the research lies in the integration of local mineral additives into a structurally optimized porous concrete matrix designed to balance load-bearing capacity and heat retention performance, forming a material that can simultaneously reduce structural dead load and enhance indoor thermal comfort; practical significance is expressed in the potential implementation of the developed technology in regional construction industries, reducing dependence on imported materials and aligning with contemporary standards of energy-efficient architecture and sustainable resource management.

METHODS

The methodological framework of the present research was developed on the basis of an integrated material science and thermophysical approach aimed at obtaining lightweight concrete with enhanced thermal stability through rational utilization of locally available mineral and technogenic raw materials, and the experimental program consisted of several interrelated stages including raw material characterization, mix design optimization, pore structure regulation, specimen preparation, curing regime control, and comprehensive testing of mechanical and thermophysical properties under standardized laboratory conditions; initially, local raw materials were selected based on geological availability, chemical composition, and potential pozzolanic activity, including expanded clay aggregate produced from regional clay deposits through rotary kiln firing at 1100–1200°C, volcanic tuff characterized by high silica content (SiO_2 58–65%), loess-derived fine mineral additives with natural aluminosilicate structure, and ash–slag waste obtained from thermal power plant combustion processes containing reactive amorphous phases, while Portland cement of strength class CEM I 42.5N was used as the primary binder and partially replaced (10–35%) with mineral additives in order to reduce clinker consumption and improve pore refinement; granulometric analysis of aggregates and fillers was performed using sieve analysis and laser particle size distribution techniques to ensure optimal packing density and minimize intergranular voids, after which the mix design was determined according to a modified volumetric method

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incorporating target density (900–1400 kg/m³), water–cement ratio (0.35–0.55), and aggregate-to-binder ratio (3.0–5.5), with superplasticizers based on polycarboxylate ethers introduced at dosages of 0.5–1.2% by weight of binder to maintain workability at reduced water content, and in selected mixtures a protein-based foaming agent was incorporated to generate a controlled closed-cell porous structure with pore diameters ranging from 0.2 to 1.5 mm, thereby reducing thermal conductivity without excessively compromising compressive strength; mixing was carried out in a forced-action laboratory mixer with sequential addition of dry components followed by gradual water introduction to ensure homogeneous distribution of mineral additives and prevent agglomeration, and fresh concrete density, slump flow, and air content were measured immediately after mixing to evaluate rheological behavior and pore formation stability; specimens were cast into cubic molds (100×100×100 mm) for compressive strength testing, prismatic molds (100×100×400 mm) for flexural strength evaluation, and plate samples (300×300×50 mm) for thermal conductivity measurement, followed by vibration compaction under controlled frequency to avoid excessive pore collapse, and curing was conducted in a humidity-controlled chamber at 20±2°C and relative humidity of 95% for 28 days, with additional series subjected to accelerated curing at 60°C to analyze hydration kinetics and early strength development; mechanical properties were determined according to standardized compression and bending tests using a hydraulic testing machine with load rate control, while density was measured by mass-to-volume ratio after oven drying at 105°C to constant weight, and thermal conductivity was evaluated using a steady-state guarded hot plate method and transient heat flow meter technique in order to determine λ-values under dry and moisture-equilibrated conditions, additionally specific heat capacity and thermal diffusivity were calculated to assess thermal inertia parameters, as thermal stability of building envelopes depends not only on conductivity but also on volumetric heat capacity (ρ·c) and time lag of heat transfer; microstructural analysis was conducted using optical microscopy and scanning electron microscopy to observe hydration products, pore morphology, and interfacial transition zones between aggregate and cement matrix, while X-ray diffraction was applied to identify crystalline phases and evaluate pozzolanic reaction progress through consumption of portlandite and formation of secondary calcium silicate hydrates, and mercury intrusion porosimetry was employed to quantify total porosity and pore size distribution in the range of 0.01–100 µm; frost resistance was assessed

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by cyclic freezing–thawing tests up to 50 cycles to examine durability under temperature fluctuations typical for continental climates, and water absorption was measured by immersion method to determine open porosity contribution to thermal conductivity increase under эксплуатацион conditions, furthermore thermal cycling tests were conducted between −20°C and +50°C to simulate seasonal variation and evaluate dimensional stability and crack resistance, while statistical analysis of experimental data was performed using regression modeling to establish correlations between density, porosity, mineral additive content, and thermophysical performance indicators, enabling determination of optimal technological parameters that balance structural strength and heat-retention capacity, and energy-saving efficiency was theoretically estimated by calculating reduction in heat flux through a standardized wall assembly incorporating the developed lightweight concrete, using Fourier's law of heat conduction and steady-state heat transfer modeling, thereby providing quantitative justification for the proposed technology in terms of operational energy demand reduction and long-term thermal stability of buildings.

RESULTS

The experimental investigations demonstrated that the incorporation of locally available mineral additives and porous aggregates significantly influenced the density, mechanical strength, pore structure characteristics, and thermophysical performance of the developed lightweight concrete compositions, and systematic variation of binder replacement ratios, aggregate gradation, and foaming parameters enabled identification of optimal technological conditions ensuring the required balance between structural capacity and thermal stability. Density measurements revealed that by adjusting the volumetric proportion of expanded clay and regulating closed-cell porosity through controlled foaming, the hardened concrete density could be reduced from conventional structural values of 2200–2400 kg/m³ to a range of 920–1380 kg/m³, while maintaining compressive strength between 8.6 and 19.4 MPa depending on binder composition and curing regime, which confirms the feasibility of producing both structural-insulating and load-bearing lightweight elements suitable for low- and mid-rise buildings. Regression analysis established a statistically significant inverse correlation between total porosity and compressive strength described by the empirical relationship: $f_c = f_0 \cdot e^{(-kP)}$ where f_c represents compressive strength (MPa), f_0 is matrix strength without additional porosity, P is

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total porosity fraction, and k is a structural coefficient experimentally determined (k ≈ 3.1–3.6). Thermal conductivity testing showed that λ-values decreased proportionally with density reduction, and the obtained range of 0.17–0.34 W/m·K represents a 35–55% improvement compared to conventional heavy concrete. The relationship between density and thermal conductivity can be approximated as: $\lambda = a\rho + b$

where $a \approx 1.7\times10^{-4}$ and $b \approx 0.02$. Volumetric heat capacity was calculated using: $C_v = \rho \cdot c$

and thermal diffusivity was determined from: $\alpha = \lambda / (\rho c)$

Microstructural examination revealed dense interfacial transition zones and secondary calcium silicate hydrate formation due to pozzolanic reactions between amorphous silica components and calcium hydroxide liberated during cement hydration. Scanning electron microscopy confirmed predominance of spherical closed pores with diameters between 0.3–1.2 mm and limited microcrack formation even after 50 freeze–thaw cycles, demonstrating improved durability under alternating temperature conditions. X-ray diffraction patterns showed partial consumption of portlandite peaks and increased intensity of C–S–H-related phases, verifying the effectiveness of mineral additives in enhancing long-term strength development, reflected in 90-day compressive strength increases of 12–18% compared to 28-day values. Frost resistance tests indicated mass loss below 3% and strength reduction not exceeding 7% after cyclic freezing, satisfying durability requirements for continental climates. Thermal modeling of a standard 300 mm wall constructed from the developed lightweight concrete demonstrated a reduction in steady-state heat flux according to Fourier's law: $q = \lambda (T_i - T_o) / \delta$ resulting in approximately 38–47% lower heat flux compared to ordinary concrete walls of equal thickness. Multi-criteria optimization identified an optimal mix composition consisting of 70–75% expanded clay aggregate, 20–25% volcanic tuff replacing cement, water–binder ratio of 0.42–0.45, and controlled foaming ensuring closed porosity fraction of 18–22%, which provides density near 1050–1150 kg/m³, compressive strength around 14–16 MPa, and thermal conductivity approximately 0.21–0.24 W/m·K, representing a rational compromise between structural reliability and energy efficiency and experimentally validating the initial hypothesis of the research.

DISCUSSION

The obtained experimental results confirm that the technological approach based on the rational integration of locally available mineral resources into a controlled porous cementitious matrix provides not only density reduction but also a synergistic improvement in thermophysical and durability characteristics, which aligns with contemporary international research trends in sustainable and energy-efficient construction materials; compared with conventional lightweight concretes produced solely through density reduction mechanisms, the developed compositions demonstrate a more balanced microstructural configuration characterized by a predominance of closed spherical pores and refined interfacial transition zones, which is essential because excessive interconnected porosity typically leads to moisture penetration and subsequent thermal conductivity increase under operational conditions, whereas the present results show limited capillary continuity and stable thermal parameters even under cyclic thermal loading; when juxtaposed with globally reported λ-values for structural lightweight concretes (0.25–0.45 W/m·K), the achieved range of 0.17–0.34 W/m·K indicates that the inclusion of volcanic tuff and pozzolanic additives contributes not merely to cement substitution but to microstructural densification of pore walls through secondary calcium silicate hydrate formation, thereby reducing solid-phase thermal bridges within the matrix, and this phenomenon supports the theoretical assumption that thermal performance is governed not only by bulk density but also by pore geometry, connectivity, and phase distribution; the exponential relationship between compressive strength and porosity $f_c = f_0 e^{(-kP)}$ observed in the regression analysis corresponds to classical material science models describing strength degradation in porous brittle materials, yet the relatively moderate value of coefficient k indicates that controlled pore morphology mitigates the negative impact of porosity on load-bearing capacity, suggesting that structural optimization rather than mere density minimization should guide technological design; furthermore, the reduced thermal diffusivity $\alpha = \lambda / (\rho c)$ confirms that the developed material exhibits enhanced thermal inertia, meaning that under diurnal temperature fluctuations typical for sharply continental climates the time lag of heat penetration increases, stabilizing indoor microclimate conditions and reducing peak energy demand for cooling and heating, which is particularly relevant in regions experiencing high summer solar gains and winter heat losses; the durability indicators, including frost resistance and limited strength reduction after thermal

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cycling, demonstrate that the microstructural refinement achieved through pozzolanic reactions decreases free calcium hydroxide content and reduces microcrack propagation potential, thereby improving long-term stability under freeze–thaw exposure, and this result is consistent with established theories linking pozzolanic activity to enhanced matrix cohesion and reduced permeability; from an environmental perspective, partial cement replacement (20–30%) significantly lowers embodied carbon emissions associated with clinker production, and when combined with reduced material mass per cubic meter due to lower density, the overall carbon footprint of structural elements decreases, contributing to sustainable development strategies and resource efficiency objectives; moreover, the technological simplicity of the proposed production method—requiring no radical modification of existing mixing and curing equipment—facilitates industrial scalability and economic feasibility, particularly in regions where transportation of heavy aggregates represents a major cost component, and thus the integration of local mineral resources simultaneously strengthens regional construction autonomy and reduces logistical energy consumption; however, it should be acknowledged that long-term field performance under real climatic conditions requires additional monitoring, especially regarding moisture-dependent thermal conductivity variations and creep–shrinkage behavior in lightweight matrices, and future research should focus on optimizing hybrid binder systems incorporating supplementary cementitious materials with nano-scale modifiers to further refine pore structure and enhance mechanical–thermal synergy; overall, the discussion confirms that the proposed technology provides a scientifically substantiated pathway toward producing thermally stable lightweight concrete using local raw materials, achieving a rational compromise between structural reliability, energy efficiency, environmental sustainability, and economic viability.

CONCLUSION

The conducted research has scientifically substantiated and experimentally validated a comprehensive technology for producing thermally stable lightweight concrete based on locally available mineral and technogenic raw materials, demonstrating that rational optimization of aggregate composition, partial cement replacement with pozzolanic additives, and controlled closed-cell pore formation enables the achievement of a structurally reliable and energy-efficient material suitable for

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modern building applications under continental climatic conditions. The obtained density range of 920–1380 kg/m³, compressive strength of 8.6–19.4 MPa, and thermal conductivity values of 0.17–0.34 W/m·K confirm that the developed compositions successfully combine reduced structural weight with enhanced thermal performance, while regression modeling established a predictable exponential relationship between porosity and compressive strength, allowing technological parameters to be adjusted according to target performance criteria. Microstructural analysis revealed the formation of dense interfacial transition zones and secondary calcium silicate hydrate phases resulting from pozzolanic reactions, which contributed to improved durability, reduced permeability, and increased frost resistance under cyclic thermal loading, thereby ensuring long-term эксплуатацион stability. The calculated reduction of steady-state heat flux through wall assemblies by up to 47% and predicted annual energy savings of 22–30% demonstrate the practical energy-efficiency potential of the proposed material, while partial cement substitution (20–30%) significantly decreases embodied carbon emissions and enhances environmental sustainability. From a technological standpoint, the developed production method remains compatible with conventional mixing and curing equipment, ensuring industrial scalability and economic feasibility, particularly in regions where transportation of traditional heavy aggregates increases construction costs. The research confirms that effective utilization of local raw materials not only reduces dependence on imported construction resources but also contributes to regional economic resilience and sustainable development strategies. Overall, the proposed technology represents a scientifically grounded, environmentally responsible, and practically implementable solution for producing thermally stable lightweight concrete capable of meeting contemporary structural, thermal, and durability requirements in energy-efficient building construction.

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