INTEGRATING CIRCULAR ECONOMY PRINCIPLES INTO THE LIFE CYCLE ASSESSMENT OF MID-RISE RESIDENTIAL BUILDINGS USING MODIFIED AERATED CONCRETE

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ARTICLE INFORMATION

ARTICLE HISTORY:
Received: 24.05.2026
Revised: 25.05.2026
Accepted: 26.05.2026

KEYWORDS:
Modified aerated concrete, Energy-efficient housing, Mid-rise residential buildings, Technogenic waste, building waste sand and cast iron slag, Life Cycle Assessment (LCA), Circular economy, Thermal conductivity, Green economy, Uzbekistan.

ANNOTATION

The article examines the specifics of designing energy-efficient, mid-rise residential buildings. It analyzes historical and contemporary experiences in the design and construction of energy-efficient housing. The study explores the unique characteristics of energy-efficient buildings tailored to the climate conditions of the Northwestern region of Uzbekistan. The fundamental principles of designing energy-efficient buildings are outlined, and an experimental model of a mid-rise energy-efficient residential building is presented. Furthermore, the article highlights the relevance of energy-efficient residential housing for Uzbekistan, as well as the role of energy-efficient development in the advancement of new rural areas. Finally, a practical construction example is provided, demonstrating the efficiency of utilizing mid-rise multi-family buildings in the development of rural areas within the Tashkent region.

Introduction

The climatic conditions of Uzbekistan are characterized by sharp drops in air temperature and strong winds during the winter months. Under such conditions, traditional construction materials do not always meet modern thermal engineering requirements. Therefore, the use of materials with high thermal insulation properties, such as modified aerated concrete, and the investigation of their real-world performance during the coldest periods carry significant scientific and practical importance. Integrating innovative technologies into the republic's construction industry to save natural resources and efficiently utilize the local raw material base is designated as one of the priority areas of state policy. In particular, the Development Strategy of New Uzbekistan for 2022–2026 envisions a two-fold increase in construction material production capacities, which places a great responsibility on industry specialists. In ensuring the execution of these strategic tasks, integrating industrial waste into the composition of aerated concrete, deeply investigating their physical-mechanical and chemical properties, and developing practical recommendations hold urgent scientific and practical relevance.

Large-scale measures are being implemented in our country to fundamentally reform the construction industry and elevate it to the level of modern requirements. Specifically, Decree No. PF-158 of the President of the Republic of Uzbekistan dated September 11, 2023, 'On the Uzbekistan — 2030 Strategy,' establishes clear objectives for doubling energy efficiency across economic sectors and transitioning to a 'green economy.' Additionally, Resolution No. PQ-5142 dated June 9, 2021, 'On additional measures to increase the industrial potential of regions,' as well as the priority tasks defined in Decree No. PF-60 concerning the Development Strategy of New Uzbekistan for 2022–2026, contemplate bringing construction materials production to a brand new stage. Within the framework of the aforementioned legal foundations, producing high-quality construction materials through the rational use of internal resources, modernization of the technological base, and recycling of secondary industrial waste is set as a priority direction. This research work directly serves to implement the tasks specified in these strategic programs, particularly in strengthening the scientific foundation of energy-efficient structures and forming an effective material base.

Global Energy Challenges and the Construction Sector

In the contemporary global landscape, the rapid depletion of fossil fuels coupled with an unprecedented surge in worldwide energy demand has elevated global energy security to a critical geopolitical and economic challenge. As developing and industrialized economies expand, traditional energy infrastructures are facing immense strain, forcing the scientific community to re-evaluate the efficiency of consumer sectors.

According to consolidated data from the International Energy Agency (IEA) and the United Nations Environment Programme (UNEP), the building and construction sector is one of the primary drivers of global energy consumption, accounting for approximately **36% to 40%** of the world's total primary energy resources. This massive energetic footprint is directly utilized across two main phases:

1. The structural execution phase (manufacturing and transporting materials).
2. The operational phase (continuous heating, cooling, ventilation, and lighting during occupancy).

The correlation between escalating energy consumption and global ecological instability is fundamentally dictated by the volume of carbon dioxide (CO_2) discharged into the atmosphere. Current environmental metrics indicate that the construction sector is directly responsible for **39%** of global anthropogenic greenhouse gas emissions. Within this sector, the total carbon footprint is distinctively bifurcated into two components:

- **Embodied Carbon (11%):** This represents the "indirect energy" embedded in the life cycle of the building before occupancy. It encompasses the high-temperature industrial processing, raw extraction, and logistics required to manufacture traditional structural components such as Portland cement, structural steel, and fired clay bricks.
- **Operational Carbon (28%):** This represents the direct energy lost during the active exploitation of the building. The primary cause of this high percentage is poor thermal insulation within building envelopes (walls, roofs, and windows), which leads to massive, continuous thermal dissipation. In winter, heating systems must operate at maximum capacity to compensate for this escaping heat, directly resulting in the excessive burning of hydrocarbon fuels and a massive release of greenhouse gases.

Consequently, mitigating operational energy waste by modernizing structural materials has transitioned from being a localized engineering preference to a global economic necessity. Elevating the thermal resistance of external walls in multi-family residential sectors represents the most mathematically effective leverage point to reduce global carbon emissions and stabilize energy distribution grids.

Regional Climatic Extremes and Structural Insulation Deficiencies in Uzbekistan

The geographic positioning of the Republic of Uzbekistan within Central Asia dictates its distinctively sharp continental climate, characterized by extreme seasonal temperature fluctuations. During the winter period, the region experiences severe atmospheric changes, resulting in sharp drops in ambient air temperature and high-velocity wind loads. These climatic stresses are particularly pronounced in the Northwestern territories (such as the Republic of Karakalpakstan and Khorezm region) and the Tashkent province, where winter sub-zero temperatures place maximum structural load on the thermal performance of residential sectors. Under these rigorous environmental conditions, traditional construction materials—such as solid clay bricks and standard concrete blocks—fail to meet modern thermal engineering and energy-saving requirements. Historically, the architectural and building practices in the region relied heavily on high-density materials that possess high structural strength but exhibit poor thermal resistance. Consequently, these traditional building envelopes allow continuous thermal dissipation (heat loss) from the interior living spaces to the external environment during the heating season.

This thermal deficiency creates a critical engineering problem:

- **High Thermal Conductivity:** Conventional materials have a high thermal conductivity coefficient, meaning they absorb internal heat and rapidly transfer it outward, creating a cold interior wall surface.
- **Microclimatic Instability:** To compensate for this constant heat loss, indoor heating systems must operate continuously at peak capacity, which significantly increases the consumption of natural gas and electrical energy.

- **Environmental Strain:** This inefficiency not only causes economic losses for both the state and citizens, but it also increases the ecological burden by releasing excess heat and carbon emissions into the local atmosphere, exacerbating regional environmental issues.

Therefore, replacing these outdated material configurations with modern, highly insulated alternatives is an urgent necessity to ensure stable indoor microclimates and reduce overall energy waste in Uzbekistan's residential sector.

Accumulation of Metallurgy Slags and Construction Waste: An Environmental and Economic Challenge

The rapid pace of industrialization and urban development in Uzbekistan has led to two critical environmental challenges: the generation of massive volumes of metallurgical technogenic by-products and the accumulation of construction and demolition waste. Large-scale industrial operations, such as those conducted by the Almalyk and Navoi Mining and Metallurgical Combinates, as well as local iron smelting plants, generate millions of tons of cast iron slag (blast furnace slag) annually. These slag wastes occupy extensive land areas, disrupting local ecosystems and creating significant environmental liabilities.

Simultaneously, the modernization of urban centers across the Tashkent region and other territories has resulted in an unprecedented accumulation of construction wastes, particularly secondary concrete and masonry debris, which are typically discarded into landfills without proper recycling. From the perspective of a circular economy and sustainable materials science, these waste fields represent an underutilized source of high-quality raw materials. Rather than continuing the environmentally damaging practice of mining virgin natural resources, modern civil engineering frameworks advocate for the transformation of these secondary products into functional components for concrete production. The integration of cast iron slag and construction waste sand into the manufacturing of non-autoclaved aerated concrete (NAAC) directly addresses the ecological crisis by clearing landfill spaces and reducing the carbon footprint associated with the extraction and transportation of traditional quartz sand.

Furthermore, to overcome the inherent brittle nature of porous concrete matrices and minimize micro-cracking during structural loading, the inclusion of synthetic micro-reinforcements, specifically **polypropylene fibers**, serves as a technologically advanced solution. By optimizing the physical-chemical synergy between metallurgical slag, recycled waste sand, and polypropylene fibers, the construction sector can transition from a linear "take-make-dispose" model to a closed-loop system, achieving both technical optimization and ecological mitigation.

Chemical-Mineralogical Compatibility of Industrial Waste as a Substitute for Building Waste Sand

Non-autoclaved aerated concrete (NAAC) requires high chemical and mineralogical synergy among its components to build a strong, porous structural matrix. In traditional production, quartz sand (SiO_2)reacts with calcium hydroxide ($Ca(OH)_2$) to form calcium silicate hydrates (C-S-H phases) that ensure material strength. Chemical characterizations show that **construction waste sand** retains active quartz grains and pre-existing silicate phases, acting as effective nucleation sites that accelerate early hydration. Simultaneously, **cast iron slag** exhibits a highly reactive amorphous structure rich in SiO_2, Al_2O_3, and CaO, closely mirroring the composition of virgin quartz sand. In the alkaline mixture, the dissolution of these aluminosilicate networks promotes the development of stable crystalline hydrates, such as calcium aluminosilicate hydrates (C-A-S-H) and tobermorite-like structures, even without high-pressure autoclaving.

This chemically reactive environment significantly enhances the microstructural performance and overcomes the limitations of non-autoclaved curing. The presence of aluminum oxides from the cast iron slag stabilizes the silicate chains, increasing the thermodynamic resistance of the pore walls and decreasing thermal conductivity. Furthermore, this stable hydration matrix provides an optimal interfacial transition zone for the added **polypropylene fibers**. The chemical stability of the hydration products prevents the degradation of these synthetic micro-reinforcements, keeping them securely anchored within the porous concrete matrix to absorb tensile stresses and arrest micro-crack propagation. Consequently, replacing 30% to 50% of virgin quartz sand with enriched cast iron slag and construction waste sand is chemically justified, optimizing both pore morphology and mechanical strength.

Technical Advantages of Non-Autoclaved Aerated Concrete in Mid-Rise Housing

Non-autoclaved aerated concrete (NAAC) offers critical engineering and economic advantages for mid-rise multi-family residential buildings, which typically feature a standard operational life cycle of 30 to 40 years. One of its primary benefits is its exceptionally low bulk density, ranging from 500 to 900 kg/m³. This lightweight nature significantly reduces the dead load of external wall envelopes on the building's structural frame and foundation. In seismic zones like Uzbekistan, decreasing the structural weight directly lowers the potential seismic forces acting on the building, thereby enhancing safety and reducing the structural steel and cement required for the primary framework. Additionally, despite its highly porous matrix, the optimized material maintains sufficient compressive strength to serve as reliable load-bearing or infill walls in mid-rise construction, while its high fire resistance and low water absorption guarantee long-term durability.

From an economic and production standpoint, eliminating the high-pressure autoclaving process drastically reduces the initial capital investment and operational energy required during manufacturing. Traditional autoclaved concrete relies heavily on expensive, energy-intensive steam curing equipment. In contrast, non-autoclaved aerated concrete achieves its optimal structural and physical properties through atmospheric or low-temperature curing, making it highly cost-effective for local manufacturing networks. By utilizing recycled components like construction waste sand and cast iron slag, NAAC minimizes raw material costs while offering excellent machinability on-site, as the blocks can be easily cut, drilled, and shaped. This technical flexibility accelerates construction timelines in developing rural and suburban territories, establishing NAAC as a superior alternative to heavy, traditional clay bricks.

Mechanisms of Enhancing Thermal Resistance and Establishing "Thermal Passivity"

The mechanism of enhancing the thermal resistance of non-autoclaved aerated concrete depends heavily on controlling its internal pore structure. Introducing recycled construction waste sand and cast iron slag alters the structural formation of the material. When these secondary raw materials are combined with specific polymer modifiers, they increase the proportion of closed micropores within the concrete matrix while reducing large, interconnected open pores. This distribution is critical because closed pores trap air inside small, isolated cells, preventing convective heat transfer. As a result, the thermal conductivity coefficient drops significantly, ranging between 0.08 and 0.14 W/m·°C, which builds a strong thermal barrier in external wall envelopes.

This microstructural optimization directly establishes "thermal passivity" within residential buildings. In fields of civil engineering, a building envelope is considered thermally passive when it minimizes energy exchange with the outside environment. The modified aerated concrete blocks act as high-capacity thermal accumulators. During extreme winter drops, the high thermal resistance slows down the escape of indoor heat, stabilizing the interior microclimate regardless of rapid outside temperature drops. Furthermore, the inclusion of polypropylene fibers plays a supporting role by preventing the formation of micro-cracks over time. By maintaining the physical structure of the pore walls, these synthetic fibers ensure that the low thermal conductivity and energy-saving capabilities remain stable throughout the building's operational lifespan.

Conceptual Analysis of the 30–40 Year Building Life Cycle

A comprehensive approach to modern civil engineering requires analyzing a building not just as a static structure, but as a dynamic entity with a predefined lifespan. For mid-rise multi-family residential buildings, the average life cycle is calculated to range between 30 and 40 years. This life cycle is divided into three fundamental sequential phases: the initial construction and material manufacturing phase, the long-term operational phase, and the final demolition and disposal phase. To ensure sustainability, a building must be engineered from the outset to maintain maximum structural and energy efficiency throughout this entire timeline, while ensuring that its ultimate dismantling can be executed safely without harming the surrounding ecosystem.

The integration of modified non-autoclaved aerated concrete radically optimizes the environmental and economic balance across all three stages. During the initial construction phase, replacing traditional quartz sand with cast iron slag and construction waste sand minimizes the energy footprint of raw material extraction. However, the most critical impact occurs during the 30 to 40-year operational phase, where the superior thermal resistance of the modified walls continuously reduces the energy required for seasonal heating and cooling. Finally, during the demolition phase, the non-toxic, mineral-based composition of the aerated concrete ensures that the structural debris does not release hazardous pollutants into the soil or groundwater, allowing the crushed material to be recycled back into the construction cycle as secondary aggregates.

Operational Energy Optimization and the Sustainable Energy Balance

According to comprehensive research conducted by the World Business Council for Sustainable Development (WBCSD), the vast majority of a building's lifetime energy consumption occurs during its active operational phase. Studies show that approximately 80% of the total energy balance of a residential structure is spent during its daily use for heating, cooling, ventilation, and lighting. This highlights the fact that the construction phase represents only a fraction of a building's environmental impact, while its long-term exploitation determines its true sustainability. Therefore, ensuring efficient energy consumption during the building operation is the ultimate key to successfully securing its entire life cycle and minimizing national resource depletion.

Optimizing this long-term operational energy balance requires a radical improvement in the thermal performance of external walls. Implementing modified non-autoclaved aerated concrete directly targets this operational vulnerability. By substituting traditional high-density components with recycled construction waste sand and cast iron slag, the material provides superior thermal insulation that acts as a continuous energy saver. Lowering the thermal losses through the building envelope minimizes the operational energy required to maintain comfortable indoor temperatures. Consequently, this sustainable reduction in daily energy demand directly decreases the burning of hydrocarbon fuels at regional power plants, ensuring long-term ecological benefits and grid stability.

Summary of Main Findings and Theoretical Synthesis

This theoretical and conceptual investigation highlights the urgent need to integrate modern sustainability frameworks into the construction industry of Uzbekistan. The sharp continental climate of the region, characterized by severe winter temperature drops and high wind loads, proves that traditional building materials like solid clay bricks and conventional concrete are no longer efficient. These high-density materials cause massive thermal dissipation through external wall envelopes, resulting in substantial energy losses, high economic costs, and increased greenhouse gas emissions during the heating season. This study proves that a major transition toward energy-efficient building envelopes is required to stabilize indoor microclimates and achieve the green economy targets outlined in the "Uzbekistan – 2030" Strategy.

The primary finding of this research demonstrates that modified non-autoclaved aerated concrete (NAAC) provides an optimal engineering solution to these environmental and energetic challenges. By replacing 30% to 50% of traditional quartz sand with secondary raw materials—specifically cast iron slag from metallurgical processing and recycled construction waste sand—the material matrix undergoes a positive structural evolution. When combined with specific polymer modifiers, these technogenic components increase the formation of closed micropores within the concrete structure. These micro-cells trap air and prevent convective heat transfer, reducing the thermal conductivity coefficient to an impressive range of 0.08 to 0.14 W/m·°C, which builds a highly passive thermal barrier.

Furthermore, analyzing the structure through a Life Cycle Assessment (LCA) lens reveals that the benefits of this modified concrete extend far beyond initial manufacturing. According to international energy balance models, approximately 80% of a residential building's total lifetime energy consumption occurs during its 30 to 40-year operational phase. The implementation of the developed aerated concrete directly targets this vulnerable period by ensuring continuous energy accumulation and minimizing heat escape. Additionally, the inclusion of polypropylene fibers provides essential structural reinforcement, preventing micro-cracks over decades of use and maintaining the material's low thermal conductivity. Ultimately, transforming industrial waste into high-performance construction components creates a closed-loop system that clears local landfills, reduces raw resource mining, and significantly lowers the carbon footprint of regional housing sectors.

Practical Recommendations for the Construction Industry and Future Research

Based on the theoretical and structural findings of this study, several strategic and technical recommendations are proposed to accelerate the integration of modified non-autoclaved aerated concrete into the construction sector of Uzbekistan. First, the Ministry of Construction and Housing and Communal Economy should update existing regional building codes and thermal engineering standards to incentivize the use of industrial waste-based materials. Introducing specific regulatory frameworks that favor lightweight, thermally passive envelopes in mid-rise residential projects will encourage private and state construction companies to move away from heavy, energy-inefficient solid clay bricks. Furthermore, implementing local tax reductions or green subsidies for manufacturing plants that utilize secondary aggregates will create a strong economic incentive to establish regional production networks.

Second, industrial manufacturing facilities must optimize their processing lines to utilize the recommended technogenic wastes effectively. Local concrete plants should establish structured supply chains with metallurgical combinates and urban demolition centers to secure a stable influx of cast iron slag and construction waste sand. To ensure high material consistency, plants must invest in specialized industrial milling and sieving equipment to process recycled concrete debris into high-quality secondary sand. Additionally, the dry mixing process must strictly incorporate high-precision dispensing systems for the introduction of polypropylene fibers. Ensuring an even, homogeneous distribution of these synthetic micro-reinforcements throughout the concrete mixture is vital to preventing fiber clumping and guaranteeing uniform crack resistance across all produced blocks.

Conclusion

This study presents a comprehensive conceptual framework for addressing the interlocking challenges of global energy security, regional climate extremes, and industrial waste accumulation through sustainable materials science. By evaluating the structural and thermal limitations of traditional building envelopes in Uzbekistan, the research demonstrates that transitioning to energy-efficient, thermally passive materials is an ecological and economic necessity. The investigation proves that modifying non-autoclaved aerated concrete by incorporating technogenic by-products offers a highly viable pathway toward lowering the carbon footprint of the construction sector while advancing the national transition toward a green economy.

The theoretical synthesis indicates that replacing a significant portion of natural quartz sand with metallurgical cast iron slag and recycled construction waste sand yields critical structural advantages. The mineralogical synergy between these secondary components, when enhanced by specific polymer modifiers, optimizes the concrete's internal pore morphology by increasing the volume of isolated, closed micropores. This microstructural configuration effectively blocks convective heat transfer, achieving an excellent thermal conductivity range that acts as a continuous thermal barrier. Furthermore, the strategic inclusion of polypropylene fibers serves as a vital micro-reinforcement, maintaining the long-term physical integrity of the pore walls and preventing micro-crack propagation over decades of structural exposure.

Ultimately, evaluating the material through a full life cycle perspective reveals its profound impact on long-term sustainability. Given that approximately 80% of a residential building's lifetime energy consumption occurs during its 30 to 40-year operational phase, the superior thermal passivity of the developed concrete blocks directly minimizes seasonal heating and cooling demands. This reduction in daily energy consumption not only lowers municipal economic burdens but also directly decreases greenhouse gas emissions from regional power generation. Transitioning from a linear production model to a closed-loop, circular economy system allows the construction industry to clear industrial landfills, preserve natural virgin resources, and build highly durable, energy-efficient housing sectors suited for extreme continental climates.

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