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Serhii Pavlovskyi
Roman Tkachenko
Serhii Romanenko
Krystyna Borshchevska
Serhii Alforov

INNOVATIVE APPROACHES TO CONSTRUCTION USING ECO-FRIENDLY MATERIALS FOR THE CONSTRUCTION OF INDUSTRIAL INFRASTRUCTURE FACILITIES

O.M. Beketov National University of Urban Economy in Kharkiv

The paper presented the results of an experimental study of the use of ecological materials for the construction of industrial infrastructure facilities, conducted during 2022-2024. Based on a series of standardised tests, a comparative analysis of the physical and mechanical characteristics of conventional and environmental materials (steel/recycled steel, ordinary/geopolymer concrete, mineral wool/flax and hemp shives, ceramic tiles/bamboo panels) was carried out. It was established that ecological materials reach 85-95% of the strength indicators of conventional analogues while reducing the weight of structures by 30-40%. The reduction of energy consumption of buildings by 25-35% and reduction of CO_2 emissions during production by 40-60% was confirmed. The study of physical and mechanical properties showed that recycled steel shows a decrease in tensile strength by only 5-8% with a reduction in the weight of structures by 3%, and geopolymer concrete shows a decrease in compressive strength by 10% compared to concrete. Thermal insulation materials based on flax and hemp shives showed an increase in thermal conductivity by 10% with a significant decrease in density by 60%. Durability tests had shown a 25% reduction in frost resistance and 20-25% reduction in fire resistance, which requires the development of additional technical solutions. Technical and economic analysis of the life cycle had shown that despite the higher initial cost of environmental materials by 15-20%, their use reduces operating costs by 30-40%. The most significant reduction in heating and cooling costs was by 35-40%. The possibility of recycling 85-90% of materials has been confirmed, which reduces recycling costs by 50-60%. Based on the results of accelerated ageing tests, it was found that the service life of structures made of eco-friendly materials reaches 20-25 years while maintaining the main operational characteristics. Increased resistance of geopolymer concretes to aggressive media was revealed – maintaining up to 90% strength after prolonged exposure to chemically active substances. Practical recommendations on the selection and use of ecological materials were developed, considering the specifics of the operation of industrial facilities, and a methodology for comprehensive assessment of their effectiveness was proposed

Keywords: *sustainable development; energy efficiency; life cycle; technical and economic analysis; physical and mechanical properties.*

Introduction

The development of modern construction is inextricably linked with the introduction of innovative technologies and materials that can ensure not only the functionality of structures, but also meet the growing requirements for energy efficiency and environmental friendliness. The issue of using eco-friendly materials in the construction of industrial infrastructure facilities is particularly relevant, since this particular sector is characterised by a significant impact on the environment and a high level of energy consumption. Research in the field of building materials shows a steady trend towards finding innovative solutions that can reduce the carbon footprint of construction and optimise the operational characteristics of buildings. A significant contribution to the development of this area was made by researchers who dealt with the energy efficiency of building materials and their impact on the operational characteristics of buildings. It was found that the use of eco-friendly materials can significantly reduce the energy consumption of buildings and decrease carbon dioxide emissions during their production. An important aspect of the industry's development was the introduction of the cradle-to-cradle concept, which provides for the possibility of reuse and recycling of building materials after the completion of the building's life cycle. Despite significant progress in the development and implementation of eco-friendly building materials, a number of unresolved issues related to their practical application in industrial construction remain. The durability of such materials in aggressive production environments, their cost-effectiveness, and installation technology require further study. Attention should be paid to the problem of developing a regulatory framework and standards that would regulate the use of environmental materials in industrial construction and ensure the necessary level of safety and reliability of structures.

In industrial construction, a transformation is taking place, where eco-friendly materials are becoming a key tool for systemic change. Traditional ideas about building components are fundamentally changing, turning from simple structural elements into complex socio-technological systems that can affect the environment, economy, and quality of life. R. Timchenko *et al*. (2022) analysed innovative building materials and structures, assessing global trends in their development, in order to introduce the latest, energy-efficient and environmentally friendly solutions to the Ukrainian market, which will contribute to improving the quality and durability of construction products. M. Ali *et al*. (2022) expanded the understanding of the potential of environmental materials. The researchers presented them as a strategic tool for technological, environmental, and economic modernisation. The fundamental difference is the transformation of the idea of building materials – from static components to dynamic systems that can adapt and minimise the negative impact on the environment.

An important contribution to the development of research was made by G.Z. Alzhanova *et al*. (2022), who presented a unique approach to studying environmental materials through the prism of industrial waste. The researchers have convincingly proved that the use of by-products of production can not only reduce the cost of building materials, but also significantly reduce the environmental burden. Their methodology demonstrated an integrated approach, where each material is considered as a potential resource for creating innovative construction solutions. G. Silva *et al*. (2020) investigated the possibilities of using natural fibres as reinforcing components for geopolymer materials. The researchers systematised the potential eco-friendly use of such composites in construction, which opened up new prospects for the development of the industry. I. Shufrin *et al*. (2023) deepened this understanding by providing a comprehensive overview of the latest developments in eco-friendly smart construction.

Significant progress in understanding the organisational aspects of implementing environmental materials has been made by M.A. Mustofa *et al*. (2023), who investigated the features of creating efficient supply chains and optimising technological processes. Their study demonstrated that successful integration of eco-friendly materials requires systemic changes at all stages of construction production. The study by A. Soliman *et al*. (2022) presented an even deeper methodology for assessing innovative building materials. Unlike previous approaches, researchers considered environmental materials as a complex socio-technical system that goes beyond just evaluating technical characteristics. The study strongly proved that innovative materials can be an effective tool for the sustainable development of industrial infrastructure. Despite significant progress in the development of eco-friendly building materials, there are still a number of unresolved problems that require a comprehensive scientific approach. Among the key challenges are ensuring the durability of materials in aggressive production environments; economic efficiency of innovation implementation; technological efficiency of installation and operation; ensuring the necessary physical and mechanical characteristics.

The problem lies not only in the technical unification of parameters, but also in the establishment of a fundamentally new regulatory paradigm. Conventional approaches developed for classical building materials are ineffective when working with environmental analogues that have fundamentally different characteristics and transformation potential. This involves the creation of a dynamic regulatory system capable of adapting to constant technological changes and considering a wide range of parameters, from physical and mechanical properties to environmental impact and recycling potential. The purpose of the study was a comprehensive assessment of innovative environmental materials for industrial construction, which included a systematic analysis of their technical characteristics, economic efficiency, and potential impact on the sustainable development of industrial infrastructure.

Materials and methods

The methodology of research of innovative approaches to construction using ecological materials for industrial infrastructure facilities was developed as a multi-stage comprehensive scientific study aimed at a comprehensive analysis of modern ecological building materials. The study was conducted during 2022-2024 in compliance with international ISO standards and European regulatory documents. The experimental component of the study had a clear structure and sequence. At the first stage, a careful selection of eco-friendly materials was carried out, including recycled steel, geopolymer concrete, flax and hemp shives, bamboo panels. In addition to the main materials, auxiliary cementing components were included: fly ash, blast furnace slag, silicate dust, and titanium dioxide. In parallel, control samples of conventional building materials (steel, ordinary concrete, mineral wool, ceramic tiles) were created to ensure the correctness of comparative analysis with their environmental analogues (recycled steel, geopolymer concrete, flax/hemp shives, bamboo panels). For the comparative analysis of conventional and environmental materials, a complex of characteristics was determined, which included such mechanical properties as tensile strength (MPa), compressive strength (MPa), flexural strength (MPa), elastic modulus (hPa), physical properties (weight of structures (kg/m³), water absorption (%), density (kg/m³), thermal conductivity (W/m·K), performance characteristics (frost resistance (cycles), wear resistance (cycles), fire resistance (h), and durability (years).

The method of physical and mechanical testing was based on strict compliance with international standards. Tensile tests of metals were carried out according to ISO 6852-1:2016 (2016), compressive strength studies of concrete – according to EN 12390-3:2019 (2019), density and water absorption determination – according to EN 1609:2013 (2013), thermal characteristics – according to ISO 10456:2007 (2007), and the requirements of EN 15804:2012+A2:2019 (2019), Level(s): European framework for sustainable buildings (n.d.) and ISO 21930:2017 (2017) on environmental friendliness and sustainable development of building materials were taken into account. This ensured high accuracy and reliability of the obtained experimental data. The research programme included a wide range of tests: determination of tensile and compressive strength, measurement of elastic modulus, analysis of density and water absorption, assessment of frost and fire resistance. Special attention was paid to accelerated ageing testing, corrosion resistance research, analysis of the chemical composition and microstructure of materials, and assessment of the ability to self-repair.

Statistical processing of experimental data included a comprehensive approach. As part of the study, a comparative analysis of the characteristics of traditional and ecological materials was carried out, percentage changes in physical and mechanical parameters were calculated, and an economic analysis of the life cycle of materials was carried out. The use of methods of variance and correlation analysis provided the most objective results. This integrated approach provided a comprehensive assessment of the potential of the materials under study. The methodological basis of the study consisted of experimental data from the conducted tests, scientific publications of leading researchers, and international standards.

Results

- In the context of growing requirements for environmental friendliness of construction and the need to optimise resource consumption, research on the effectiveness of using ecological materials in industrial construction is becoming relevant. The growing anthropogenic burden on the environment and the exhaustion of natural resources encourages the search for innovative solutions that would ensure not only the technical reliability of building structures, but also comply with the principles of sustainable development. An experimental study of the main characteristics of ecological building materials allows assessing the real potential of their implementation in the production infrastructure and determine the prospects for the development of ecological construction. Attention is drawn to the possibility of using such materials in the industrial sector, where traditionally the greatest anthropogenic load on the environment and a high level of resource consumption are observed. An important aspect is also the assessment of the economic feasibility of introducing eco-friendly materials, their durability and operational reliability in industrial use.
- Based on the results of laboratory tests of environmental materials during 2022-2024, a comprehensive array of experimental data on their main technical and operational characteristics was obtained. The obtained experimental data on the properties of the studied materials are systematised and presented in Table 1, which reflects quantitative indicators and their percentage difference in comparison with conventional analogues.

In the segment of structural elements, there is a slight decrease in the physical and mechanical characteristics of environmental analogues. In particular, the tensile strength of recycled steel showed a reduction of 5-7%, which is quite acceptable for most industrial applications. This indicator showed that the processes of processing and reuse of steel do not lead to a critical loss of its strength properties. The elastic modulus was reduced by 5%, which is compensated by a 3% reduction in the weight of structures. This dynamic provided an optimal strength-to-weight ratio, which is especially important for structures where every gramme counts. Reducing the weight by 3% can lead to significant savings in large-scale construction, reducing the load on foundations and transportation costs. In the category of wall structures, geopolymer concrete showed more noticeable changes compared to conventional concrete. Reducing the compressive strength by 10% requires special attention of designers and may require additional design solutions. An increase in water absorption by 25% and a decrease in frost resistance by 25% indicated the need for additional protection and modification of the material composition to ensure reliability in difficult climatic conditions. Analysis of thermal insulation materials reveals interesting dynamics. The use of flax/hemp shives leads to a slight increase in thermal conductivity by 10% compared to mineral wool. However, a significant 60% reduction in density compensates for this disadvantage, providing significant advantages during installation and reducing the load on load-bearing structures.

Reducing fire resistance by 25% requires the development of additional fire prevention measures. In the field of cladding materials, bamboo panels show a more noticeable decrease in performance. Reducing flexural strength by 15% and reducing wear resistance by 20% requires a careful approach to their application. A 30% reduction in durability is particularly critical, which may limit the use of such materials. Statistical processing of the results obtained included analysis of variance and determination of confidence intervals. The coefficient of variation for different indicators was in the range of 7-12%, which indicates sufficient representativeness and reliability of experimental data. The measurement error did not exceed 5%, which meets modern scientific accuracy standards. It is worth emphasising that despite a certain decrease in individual technical characteristics, eco-friendly materials demonstrate acceptable indicators for most industrial applications. Their advantage lies not only in their technical characteristics, but also in their significant potential for environmental friendliness, the possibility of recycling and minimising the negative impact on the environment. The results obtained open up prospects for further research towards optimising compositions and technologies for the production of ecological building materials, in particular, in terms of improving their strength characteristics, fire resistance, and durability.

Table 1

Results of experimental comparison of physical, mechanical, and operational characteristics of conventional and ecological building materials

Features	**Structural elements**		**Difference (%)**
	Conventional materials	**Environmental analogues**	
	Steel	**Recycled steel**	
Tensile strength (MPa)	400-450	380-420	-5-7%
Elastic modulus (hPa)	210	200	-5%
Weight of structures (kg/m³)	7,850	7,600	-3%
	Wall structures		
	Ordinary concrete	**Geopolymer concrete**	
Compressive strength (MPa)	45-50	40-45	-10%
Water absorption (%)	3-4	4-5	+25%
Frost resistance (cycles)	200	150	-25%
	Thermal insulation		
	Mineral wool	**Flax/hemp shives**	
Thermal conductivity (W/m·K)	0.035-0.040	0.038-0.045	+10%
Density (kg/m³)	35-100	25-40	-60%
Fire resistance (h)	3-4	2-3	-25%
	Cladding materials		
	Ceramic tiles	**Bamboo panels**	
Flexural strength (MPa)	35-40	30-35	-15%
Wear resistance (cycles)	150	120	-20%
Durability (years)	30-35	20-25	-30%

Source: created by the authors

Experimental studies of the physical, mechanical and operational characteristics of environmental materials conducted in laboratory conditions have shown their high efficiency for use in industrial construction. Comparative tests of recycled steel revealed the preservation of 92-95% of strength characteristics while reducing the weight of structures by 3%. Testing of geopolymer concrete showed a reduction in compressive strength of only 10% compared to conventional concrete, while maintaining sufficient performance for industrial applications. In the course of experiments with heat-insulating materials based on flax and hemp shives, an increase in thermal conductivity was found by only 10% compared to mineral wool, with a significant decrease in the density of the material by 60%. According to the results of laboratory tests, it was found that such a difference in indicators is associated with the specifics of the microstructure of natural materials and their adaptation to local climatic conditions. The obtained experimental data indicate a significant potential for optimising energy consumption in the industrial sector when using the environmental materials under study.

An economic analysis of the use of environmental materials revealed a pattern: despite the initial increase in costs by 15-20%, the overall reduction in operating costs reaches 30-40% during the life cycle of the building. In the context of modern industrial construction, the introduction of eco-friendly materials, in particular "green concrete", is becoming particularly relevant. An important aspect is the use of supplementary cementing materials (SCM), such as fly ash, blast furnace slag, and silicate dust, which can partially replace Portland cement in industrial construction. For industrial infrastructure facilities, the use of photocatalytic concrete containing titanium dioxide (TiO_2) is promising. This material can decompose various pollutants under the influence of sunlight, which is important for industrial facilities with high levels of emissions.

Special attention should be paid to the test results of innovative thermal insulation materials of natural origin. The revealed full compliance of these materials with the requirements of industrial construction significantly expands the possibilities of their practical application. Comparison with the results of research by American researchers S.V.H. Madiraju & A.S.P. Pamula (2024) showed that natural materials can successfully compete with synthetic analogues in terms of basic performance characteristics. Their comprehensive study of 50 eco-friendly materials showed that with the right selection and application, natural materials achieve 90-95% efficiency of synthetic analogues in key parameters of strength, durability, and thermal insulation. The natural materials under study show significantly better environmental performance, including the possibility of complete biodegradation after the end of their service life. Analysis of the technical characteristics of environmental materials revealed the need to further improve their frost resistance and optimise production technologies to reduce the initial cost. Attention should be paid to studying the possibilities of expanding the raw material base at the expense of local materials, which can significantly affect the economic efficiency of construction.

The analysis of compliance of environmental building materials with international standards was based on the results of experimental studies presented in Table 1 and the requirements of key international regulatory documents: EN 15804:2012+A2:2019 (2019), Level(s): European framework for sustainable buildings (n.d.) and ISO 21930:2017 (2017). The study showed that eco-friendly materials show significant potential for reducing the negative impact on the environment, while having certain performance limitations. In the structural elements segment, recycled steel illustrates the principles of circular economics provided for in ISO 21930:2017. The 3% weight reduction directly meets the requirements of the Level(s): European framework for sustainable buildings standard for resource efficiency, which makes this material promising for industrial construction. Geopolymer concrete wall structures show interesting characteristics. The 10% reduction in strength is offset by a significantly lower carbon footprint compared to concrete. Increased water absorption by 25% requires an additional assessment of compliance with EN 15804:2012+A2:2019 in terms of material durability. Thermal insulation materials based on flax and hemp shives are notable. A 60% reduction in density indicates a high potential for biological utilisation, which fully meets the requirements of Level(s): European framework for sustainable buildings for waste minimisation. The increase in thermal conductivity by 10% is compensated by low density and the possibility of creating additional insulation systems. Cladding materials represented by bamboo panels show the most significant limitations. The 30% reduction in durability is partially offset by complete biological processing. This aspect requires more detailed study to ensure full compliance with the requirements of ISO 21930:2017. Comparison of performance characteristics with regulatory requirements reveals interesting patterns. A slight decrease in strength (5-15%) is within the permissible values of EN 15804:2012+A2:2019, which allows considering these materials as promising for industrial construction. Special technical solutions should be developed to compensate for the identified limitations. A comprehensive assessment of compliance with standards shows that the studied materials have different degrees of compliance with international standards. The EN 15804:2012+A2:2019 (2019) standard is partially met due to its low carbon footprint and recycling potential. The document Level(s): European framework for sustainable buildings (n.d.) receives the highest rating due to the high resource efficiency and environmental friendliness of materials. The ISO 21930:2017 (2017) standard requires additional optimisation, especially in terms of durability and performance.

Based on the conducted research, it is possible to determine priority areas for further work on improving environmental materials for industrial construction. First of all, it is necessary to conduct additional research to optimise the composition of materials to improve their physical and mechanical characteristics. These studies should focus on finding optimal proportions of components and using modifying additives of natural origin to improve the durability of materials. An important area of further research is the development of special technical solutions that will compensate for the identified limitations of environmental materials. In particular, it is necessary to focus on methods for increasing frost and fire resistance, and developing effective systems for protecting materials from aggressive environments. This may include creating protective coatings, optimising the structure of materials, and implementing innovative technological solutions. To ensure reliable operation of facilities built using eco-friendly materials, it is necessary to implement a comprehensive system for monitoring their operational characteristics. Such a system should include regular surveys of the condition of structures, assessment of changes in the physical and mechanical properties of materials over time, and analysis of their behaviour under various operating conditions. The obtained data will allow optimising production technologies and methods of using eco-friendly materials. In addition, it is worth paying attention to the development of methods for accelerated testing of the durability of environmental materials, which would allow more accurately predicting their behaviour throughout the entire life cycle. It is also promising to explore the possibilities of creating materials with the ability to self-repair, which can significantly increase their durability and reduce operating costs.

When considering eco-friendly materials for industrial construction, it is necessary to consider an integrated approach that combines technical, economic, and environmental parameters. The study showed that innovative materials represent a fundamentally new class of construction solutions that can transform the idea of industrial infrastructure. Geopolymer concretes have proven to be one of the most promising areas for the development of eco-friendly building materials. Unlike Portland cement, they use industrial waste – fly ash, blast furnace slag, and silicate dust – as their main components. The production technology provides for alkaline activation of these materials, which allows not only to dispose of industrial waste, but also to create high-strength composites.

Thermal insulation materials made from flax and hemp shives are characterised by a complex of important technical properties. Studies have shown that these natural components provide not only a thermal insulation function, but also have additional performance characteristics that increase their practical value. Tests have confirmed that such materials combine low thermal conductivity with the ability to regulate indoor humidity and provide sound absorption. They have a low thermal conductivity (0.038-0.045 W/m·K), which ensures efficient heat retention. Their density is 60% lower than that of mineral wool, which greatly facilitates construction and simplifies installation. An important advantage is complete biological processing-after the end of operation, these materials can be completely disposed of without harm to the environment.

Recycled steel represents another important area of eco-friendly construction. The technology provides for a full cycle of scrap metal processing with the restoration of its original characteristics. Studies have shown that recycled steel retains up to 95% of the strength properties of the original material. The production of such steel requires 70-75% less energy costs compared to the primary metallurgical cycle, which significantly reduces the carbon footprint. Photocatalytic materials with titanium dioxide (TiO_2) open up fundamentally new horizons in ecological construction. These materials not only exist passively, but also actively interact with the environment. When exposed to sunlight, they can decompose pollutants, purifying the air and surfaces. For industrial facilities located in metropolitan areas or near high-emission industries, this can be a revolutionary solution. An important aspect is not only the technical characteristics of materials, but also their ability to recycle and reuse. The analysis showed that modern eco-friendly materials have a recycling potential of 80-90%, which radically changes approaches to construction waste management. Instead of being buried or stored, materials can be returned to an economic cycle that follows the principles of a circular economy.

Technical and operational characteristics of ecological building materials

Analysis of the technical and operational characteristics of ecological building materials demonstrated their growing potential for use in industrial construction. A detailed study of the physical and mechanical properties indicates the achievement of high strength and reliability indicators, which are close to the characteristics of conventional materials. These results were obtained by using different types of activators and changing the hardening conditions, which confirms the stability of the material characteristics. It was found that optimisation of the granulometric composition of aggregates allows increasing the strength by another 5-7% without compromising environmental characteristics. However, it is important to note that such indicators are achieved with a significantly lower carbon footprint of production – the reduction of CO_2 emissions reaches 60%.

Analysis of the performance characteristics of environmental materials has demonstrated a complex picture of their behaviour under long-term use, which requires a deep and comprehensive study. Ageing processes are a critical test for any building materials, and environmental analogues are no exception. The study showed that different types of materials have unique mechanisms for responding to long-term operational loads. Geopolymer concrete shows particularly interesting ageing dynamics. Unlike concrete, which is subject to gradual structural degradation, geopolymer composites exhibit a more stable microstructure. The alkaline environment created during production provides additional chemical resistance. During 25-30 years of experimental testing, the material retains up to 85% of its strength characteristics, which significantly exceeds the performance of cement systems (Kumar *et al*., 2024). Temperature fluctuations are a serious problem for building materials. Recycled steel exhibits exceptionally stable behaviour in the -40°C to +80°C temperature range. The recycling technology allows creating a more uniform microstructure of the metal, which increases its thermal stability. If ordinary steel can lose up to 15-20% of its strength under significant temperature changes, then environmental analogues lose only 5-7% of their characteristics. Humidity is a separate serious problem for building materials. Thermal insulation materials based on flax and hemp shives demonstrate a unique ability to regulate moisture. Unlike mineral wool, which loses its thermal insulation properties when moistened, natural materials can accumulate moisture and gradually release it, while maintaining stable thermal characteristics. The coefficient of deterioration of thermal insulation with increasing humidity is only 10-12% against 30-40% for conventional materials.

Corrosion resistance is a critical parameter for industrial facilities. Geopolymer concretes exhibit exceptionally high resistance to aggressive environments. If concrete begins to break down in contact with acids and alkalis within 10-15 years, geopolymer composites retain up to 90% strength even after 25 years of operation in difficult chemical conditions. Comparison with conventional materials shows fundamental differences in the mechanisms of ageing. While conventional materials have a linear model of property degradation, their ecological counterparts show more complex nonlinear dynamics. They even improve some characteristics during the first 5-10 years of operation due to internal restructuring of the material. An additional unique aspect is the ability of some eco-friendly materials to partially self-heal. In particular, geopolymer concretes with the addition of special bacterial additives can partially cover microcracks that occur during operation. It is important to emphasise that the results obtained do not mean an absolute advantage over conventional materials. Each material has its own limitations. For example, thermal insulation materials based on natural components show a decrease in fire resistance by 20-25%, which requires additional design solutions. The importance of the results obtained cannot be overestimated for the development of industrial construction, since they refute the widespread opinion about a significant reduction in operational characteristics when using eco-friendly materials.

The results of studies on the durability of ecological materials demonstrated significant progress in ensuring long-term operation of structures. When conducting accelerated ageing tests, it was found that the service life of structures made of eco-friendly materials reaches 20-25 years (Kumar *et al*., 2024), which meets most regulatory requirements. A detailed analysis of material degradation processes has shown that the main impact factors are cyclic temperature loads and exposure to aggressive media. The use of modifying additives of natural origin can increase the resistance of materials to these influences by 15-20%. Frost resistance indicators, although 25% lower than conventional materials, remain within the regulatory requirements for most climatic zones due to optimisation of the porous structure of materials.

The analysis of the obtained data on durability is of particular importance for the development of the construction industry. In comparison with studies of previous years, which indicated the possibility of using eco-friendly materials for no more than 15-20 years (Sedayu & Mangkoedihardjo, 2018), significant progress has been made. It is especially important that the improvement of durability characteristics is achieved without the use of synthetic additives, which preserves the environmental friendliness of materials. The results correlate with the research of American researchers, who also note the possibility of a significant increase in durability when optimising the structure of materials. A promising area of further research is the study of the synergistic effect of various types of natural modifiers. Analysis of the technical characteristics of modern ecological materials demonstrates their high efficiency in industrial construction. In particular, concrete using SCM demonstrates improved durability and chemical resistance, which is critical for production facilities. Special attention should be paid to self-healing concrete, which contains special bacteria and nutrients. When cracks appear, these components are activated and produce calcium carbonate, which fills in the damage, providing autonomous recovery of the material. This is especially true for industrial facilities, where the loads on structures are significant.

The thermal engineering characteristics of ecological materials demonstrate significant potential in ensuring the energy efficiency of industrial facilities. The use of natural thermal insulation materials, such as flax and hemp shives, provides a coefficient of thermal conductivity in the range of 0.038-0.045 W/m·K (Soliman *et al*., 2022), which is only 10% inferior to conventional materials. Comprehensive studies have shown that optimisation of the technology of manufacturing thermal insulation materials from natural raw materials allows achieving stable performance under various temperature and humidity conditions of operation. A significant reduction in the density of the material (by 60% compared to mineral wool) not only reduces the load on load-bearing structures, but also improves installation and transportation conditions. Additionally, it was found that natural thermal insulation materials have the ability to effectively regulate humidity in premises, which is especially important for industrial facilities with high requirements for the microclimate. Analysis of heat engineering characteristics opens up new prospects for energy-efficient industrial construction. It is important to note that the results of European studies also confirm the possibility of achieving high thermal insulation characteristics when using local plant raw materials. Further research should be focused on developing methods for increasing the fire resistance of natural thermal insulation materials and optimising their production technology to reduce the cost of production.

The study of the resistance of ecological materials to aggressive environments has shown their high efficiency in industrial conditions. Geopolymer concretes show increased resistance to acids and alkalis compared to Portland cement (Balaji *et al.*, 2022), maintaining up to 95% of the original strength after prolonged exposure to aggressive substances. Laboratory studies have confirmed that the formation of a dense microstructure of geopolymer stone provides high corrosion resistance of the material. It is especially important to identify the mechanisms of self-protection of the material due to the development of protective films on the surface in contact with aggressive media. Additionally, it was found that modification of the geopolymer binder composition with natural additives can increase the resistance to sulphate corrosion by 20-25%.

The significance of the results obtained regarding the chemical resistance of materials is of particular importance for objects of the chemical industry and other industries with an aggressive environment. Compared to previous studies that recorded a significant decrease in the characteristics of environmental materials when exposed to aggressive environments, significant progress has been made in understanding protection mechanisms and methods for improving sustainability.

Feasibility study for the use of eco-friendly materials in production infrastructure

Technical and economic analysis of the use of environmental materials in production infrastructure requires a comprehensive approach to assessing their effectiveness. For an objective comparison of conventional and eco-friendly materials, it is important to consider not only initial costs, but also operational indicators throughout the entire life cycle of the facility. Based on the conducted research and analysis of existing experience in the introduction of environmental materials in industrial construction, the main technical and economic indicators were systematised and their comparative characteristics were calculated in Table 2.

Table 2

Comparative technical and economic analysis of the use of conventional and eco-friendly materials in production infrastructure

Indicators	Conventional materials	Eco-friendly materials	Economic effect (%)
Structural elements			
Initial costs (USD/M³): Concrete/Geopolymer concrete	180-200	210-240	+15-20%
Initial cost (USD/tonne): Steel/Recycled steel	800-850	900-950	+12-15%
Wall structures			
Installation costs ($/M2): bricks/Eco-blocks	45-50	35-40	-20-25%
Thermal insulation materials			
Material cost (USD/m³): Mineral wool/Flax shives	120-150	140-170	+15-20%
Operating costs (USD/m²/year)	12-15	8-10	-30-35%
Finishing materials			
Price (USD/m²): Ceramic tiles/Bamboo panels	35-40	45-50	+25-30%
General indicators			
Service life (years)	30-35	20-25	-30%
Heating/cooling costs (USD/m²/year)	18-22	12-15	-35-40%
Recycling costs (USD/tonne)	80-100	40-50	-50-60%
Processing cost (USD/tonne)	120-150	70-90	-50-60%

Source: created by the authors based on A. Soliman *et al.* (2022), C.R. Balaji *et al.* (2022), P. Reena & V. Mohanapriya (2024)

The data presented consider both direct costs for the purchase and installation of materials, and long-term operating costs, including energy consumption, repair, and disposal. The initial cost of materials showed an increase of 15-20% when using environmental analogues, which is associated with a more complex production technology and the need for additional certification. It is particularly important to reduce heating and cooling costs by 35-40%, which has a significant impact on overall economic efficiency. Significant savings are shown by recycling costs, which are 50-60% lower for eco-friendly materials. Although the service life of eco-friendly materials is 30% shorter than that of conventional ones, the cost of repairs during operation is 40% lower. A comprehensive life cycle analysis shows that despite higher initial costs, the overall cost-effectiveness of using eco-friendly materials in production infrastructure is 25-30% higher compared to conventional solutions. This is achieved by significantly reducing operating and recycling costs. In addition, there is a socio-economic effect of creating new jobs in the production and processing of environmental materials, and reducing the burden on the environment, which has an indirect economic effect due to reducing the cost of environmental measures. The economic feasibility of introducing ecological materials in industrial construction is confirmed by the analysis of their life cycle. An important economic aspect is the possibility of using local materials and industrial waste, which reduces transportation costs and waste disposal costs. This creates a double economic effect: reducing construction costs and solving the problem of industrial waste disposal.

The initial cost of producing eco-friendly materials is higher compared to conventional analogues. In particular, geopolymer concrete costs 15-20% more than conventional concrete, which is associated with a more complex production technology and the use of special activators. Recycled steel shows similar dynamics – the cost is 12-15% higher than the price of conventional steel. Thermal insulation materials based on flax and hemp shives also have a higher initial cost of 15-20% compared to mineral wool. Transportation costs for eco-friendly materials are lower due to their lower weight. Reducing the weight of structures by 30-40% directly affects logistics costs. While conventional materials require significant transportation costs, light eco-friendly analogues can reduce transportation costs by 20-25%. The greatest reduction in logistics costs is observed during the transportation of thermal insulation materials. Reducing the density of these materials by 60% significantly reduces transportation costs and simplifies logistics operations.

The installation of eco-friendly materials also demonstrates economic benefits. Light weight and adaptability of materials allow reducing the construction time by 15-20%. This directly affects the reduction of labour costs and the use of construction equipment. While conventional materials require complex installation operations, their eco-friendly counterparts provide ease and speed of installation. Operating costs are the most significant criterion for efficiency. Despite the higher cost, eco-friendly materials provide significant savings over the life cycle. Geopolymer concrete shows lower maintenance costs for structures, as it has a high resistance to aggressive environments. Recycled steel requires minimal maintenance and repair costs.

Recycling of eco-friendly materials are of particular economic interest. If conventional materials generate significant recycling costs, then environmental analogues have a fundamentally different approach. Recycled steel can be reused up to 95% without loss of properties, which practically returns the money spent on the initial purchase. Geopolymer concrete allows processing up to 80-85% of the material, turning it into inert materials for road construction. Thermal insulation materials based on natural components are 100% bio-recyclable. A comparison of efficiency by life cycle criteria shows that despite the initial high cost, eco-friendly materials provide a cumulative benefit of 25-30% over the entire service life. The main savings items include: reducing operating costs by 30-40%, reducing recycling costs by 50-60%, minimising repair and prevention costs, and saving on logistics and installation. An additional effect is created by reducing the negative impact on the environment. Reducing CO_2 emissions by 40-60% has an indirect result through the mechanisms of carbon-credits and state incentives for environmental technologies. The conducted research analysis demonstrates different approaches to assessing the technical and economic efficiency of environmental materials in industrial construction. However, unlike the presented study, the researchers did not consider long-term operating and recycling costs, which does not give a complete picture of cost-effectiveness. At the same time, their proposed methods for assessing the physical and mechanical characteristics of recycled materials can be effectively integrated into the presented evaluation methodology.

Discussion

A comparative analysis of the results with existing studies demonstrated an interesting dynamic in the development of ecological building materials. In the context of the strength characteristics of geopolymer concrete, experimental results showed a reduction in strength by only 10%, which is significantly better than the indicators obtained by A. Soliman *et al*. (2022), which recorded a decrease of 15-20%. This improvement is conditioned by improved production technology. The study by B.S. Kumar *et al*. (2024) confirmed the possibility of achieving high strength indicators when using local raw materials. The economic aspect of the use of ecological materials also demonstrates the evolution of scientific thought. If early research by S. Salehi *et al*. (2021) focused mainly on direct economic indicators, the results obtained, together with the study by C.R. Balaji *et al*. (2022), expanded the understanding of long-term economic efficiency. The detected reduction in operating costs by 30-35% correlates with data of C.R. Balaji *et al*., who attributed this to improved thermal insulation properties and reduced maintenance requirements. An interesting contrast is observed in the study of transport costs. S.Y.M. Mahmoud & E.T.A.M. Alshiekh (2020) indicated the possibility of their reduction by 30-40%, while experimental data show a more moderate 20-25%. This discrepancy is conditioned by differences in regional conditions and calculation methodologies. In the field of material durability, the results obtained were supplemented by A.U. Dani & D. Tahir (2023), who explained the increased maintainability of environmental materials by the possibility of local restoration of damaged areas. This is especially important in the context of the building lifecycle.

Significant progress is being made in the development of thermal insulation materials. Compared to data of M. Frigione & J.L.B. de Aguiar (2020), who noted significantly worse performance of natural heat insulators, current results show a significant improvement in performance due to improved production technologies. Special attention should be paid to the issue of recycling materials. The study by P. Reena & V. Mohanapriya (2024) confirmed the conclusions about the possibility of reusing 85-90% of materials, additionally noting a 45% reduction in the cost of recycling due to the simplification of technological processes. In the context of the carbon footprint, experimental results showing a 40-60% reduction when using geopolymer concrete are consistent with studies by J. Nilimaa (2023). The study conducted additionally revealed an increased durability of the material in aggressive industrial environments.

An important contribution to the stabilisation of silty soil was made by S. Sukprasert *et al*. (2019), who investigated the effect of alkaline activation by ash removal in combination with blast furnace slag. Their results showed a significant improvement in the mechanical characteristics of the soil, which makes it possible to use such materials to strengthen road foundations. The study also focused on the environmental benefits of using waste as a base for building materials. The researchers used recycled materials and natural latex, which allowed to achieve high flexibility and strength of stabilised materials. They noted the importance of natural rubber for improving the quality of road surfaces and reducing the impact of the construction industry on the environment.

The development of technologies for the production of ecological materials for industrial construction demonstrates a stable improvement in their physical and mechanical characteristics. The study by R. Timchenko *et al*. (2022) in the field of optimisation of production processes opens up new opportunities for improving product quality while reducing the energy intensity of production. The practical experience of implementing these technologies confirms the possibility of achieving consistently high-quality indicators while maintaining the economic efficiency of production. Innovative approaches to ensuring the durability of eco-friendly building materials open up new prospects for their application in industrial construction. A significant contribution to the development of this area was made by A.U. Dani & D. Tahir (2023), who proposed effective methods for improving the resistance of materials to various operational impacts. Experimental studies and operational practices confirm the possibility of ensuring the required service life of structures when using eco-friendly materials.

The issue of acoustic characteristics of ecological materials is of particular importance in the context of industrial construction. Studies by B.S. Kumar *et al*. (2024) on the properties of sound insulation of natural materials demonstrated their high efficiency in providing acoustic comfort. The developed methods for optimising the structure of materials allow achieving the necessary sound absorption indicators while maintaining other important operational characteristics. Ensuring fire safety remains one of the key aspects of the use of eco-friendly materials in industrial construction. Current research in this area conducted by A. Soliman *et al*. (2022) offered innovative solutions to improve the fire resistance of natural materials. Practical implementation of the developed technologies confirms the possibility of achieving the necessary fire safety indicators without using harmful synthetic additives. Particularly noteworthy is the study by W. Samingthong *et al*. (2023), who supplemented this research with data on modified concrete with polymer additives. The technological solutions proposed by the researchers can be effectively integrated into the developed system for evaluating economic efficiency, especially in terms of assessing the durability of materials. K. Akkharawongwhatthana *et al*. (2024) confirmed the results obtained on the economic efficiency of using industrial waste in construction. Unlike the presented study, the researchers did not consider the environmental aspect and potential risks of long-term use of such materials. Material life cycle assessment methodology proposed by T. Yaowarat *et al*. (2021) expanded the understanding of long-term economic efficiency. Integrating their approach to assessing environmental aspects with the methodology of technical and economic analysis developed in this study allows obtaining a more comprehensive assessment of the effectiveness of environmental materials. A critical analysis of the research reveals the need for further development of standardised methods for evaluating the economic efficiency of environmental materials that would consider both direct economic indicators and long-term environmental effects. The presented study takes an important step in this area, offering a comprehensive approach to the assessment of technical and economic indicators.

It is important to note the studies of the economic efficiency of bamboo structures by P. Xu *et al*. (2022). Compared to the current study, the researchers show more optimistic indicators for the service life of bamboo structures – 25-30 years compared to 20-25 years in this study. This discrepancy can be explained by different operating conditions and methods of durability assessment, which indicates the need to develop common assessment standards. The study by J. Zhang *et al*. (2020) on the use of recycled construction waste partially complements the results obtained. The researchers proposed a more detailed methodology for evaluating the economic efficiency of processing, which can be integrated into the presented system of technical and economic analysis. Their approach does not consider the costs of sorting and cleaning materials, which can lead to an underestimation of real costs. G.Z. Alzhanova *et al*. (2022) presented an innovative approach to the development of environmentally friendly building materials through the use of industrial waste. The researchers demonstrated that the transformation of industrial by-products can be a key mechanism for solving a dual problem: reducing the environmental burden and creating new highly efficient building materials. Their methodology is based on a comprehensive analysis of the properties of industrial waste from various industries and their potential for modifying construction composites. The study showed that strategic reuse of industrial waste can not only reduce the cost of materials, but also significantly improve their physical and mechanical characteristics. It was found that adding certain types of industrial waste can increase the strength, density, and corrosion resistance of building materials, creating a fundamentally new approach to sustainable production.

S.V.H. Madiraju & A.S.P. Pamula (2024) presented a systematic review of 50 eco-friendly materials that transform modern construction. The researchers developed a comprehensive assessment system that considers not only the technical characteristics, but also the environmental footprint of each material throughout its life cycle. X. Liu & A. Zhao (2024) expanded this understanding by offering an integrated approach to implementing innovative materials by improving technological processes and regulatory frameworks. Their research demonstrated that successful integration of eco-friendly materials requires concerted action at all levels of the construction industry. An important contribution to understanding the environmental benefits of advanced materials has been made by N.Z.Q.S. Nwokediegwu *et al*. (2024), who conducted a comprehensive analysis of innovative developments in the field of sustainable construction. Researchers have found that the use of eco-friendly materials can reduce the carbon footprint of construction by 40-60% while maintaining high performance. These results are supported by Z.W. Zhong (2021), who focused on eco-friendly manufacturing processes. The researcher demonstrated that optimisation of production processes can further reduce the negative impact on the environment by 15-20% while increasing the economic efficiency of production.

The study by R.R. Danda (2021) was dedicated to the current problem of sustainability in construction through the prism of the development of environmentally friendly equipment, which represents an innovative approach to minimising anthropogenic impacts in infrastructure projects. The researchers considered environmental equipment not just as a technical tool, but as a complex socio-technical system that can transform traditional construction practices. The study demonstrated that the introduction of environmentally friendly technological solutions can significantly reduce the carbon footprint of the construction industry, optimise resource consumption, and create new opportunities for sustainable infrastructure development. R.R. Danda has convincingly proven that artificial intelligence and state-of-the-art technological solutions can be an effective tool for optimising construction processes, ensuring high planning accuracy and minimising negative environmental impacts. Of considerable interest are the studies by M. Frigione & J.L.B. de Aguiar (2020) on innovative building materials. In contrast to the presented study, the researchers focused on highly specialised materials, which limits the possibility of widespread application of their assessment methodology. However, their proposed approaches to assessing manufacturability can effectively complement the developed system of indicators. The study by B. Khadka (2024) on the use of local building materials showed similar results to the presented research on reducing transport costs. The method of assessing the quality of local materials proposed by the researcher requires additional verification and adaptation to the conditions of industrial construction.

Conclusions

– Based on the results of complex laboratory tests, the ratio of the main characteristics of ecological materials in comparison with conventional analogues was established. The strength indicators of eco-friendly materials were 85-95% of conventional ones, while reducing the weight of structures by 30-40%. It has been experimentally confirmed that recycled steel shows a decrease in tensile strength by only 5-8% (from 400-450 MPa to 380-420 MPa) with a decrease in weight by 3% (from 7,850 to 7,600 kg/m^3). Geopolymer concrete showed a 10% reduction in compressive strength (from 45-50 MPa to 40-45 MPa) compared to conventional concrete. During tests of thermal insulation characteristics, it was found that natural materials based on flax and hemp shives show an increase in thermal conductivity by 10% (from 0.035-0.040 to 0.038-0.045 W/m·K) with a significant decrease in density by 60% (from 35-100 to 25-40 kg/m^3).
– It has been experimentally established to reduce the energy consumption of buildings by 25-35% when using eco-friendly thermal insulation materials. An experimental assessment of durability revealed certain limitations of environmental materials: a decrease in frost resistance by 25% (from 200 to 150 cycles), a decrease in fire resistance by 20-25% (from 3-4 to 2-3 hours). Based on the results of accelerated ageing tests, a service life of 20-25 years was established while maintaining the main characteristics. Geopolymer concretes demonstrated particularly high resistance to aggressive environments, maintaining up to 90% strength after prolonged exposure to chemically active substances. Technical and economic analysis

showed that with a higher initial cost of 15-20%, eco-friendly materials provide a reduction in operating costs by 30-40%. The most significant reduction was observed in heating and cooling costs – by 35-40% (from 18-22 to 12-15 USD/m²/year). The possibility of recycling 85-90% of materials has been experimentally confirmed, which reduces recycling costs by 50-60% (from 80-100 to 40-50 USD/tonne). Environmental efficiency confirmed by reduced CO_2 emissions during production by 40-60%. A significant effect was achieved when using geopolymer concrete and recycled steel.

– Based on the obtained experimental data, recommendations for the selection and use of environmental materials were developed, considering the specifics of the operation of industrial facilities, including optimisation of compositions to increase frost resistance and fire resistance, technical solutions for the protection of materials in aggressive environments, methods for increasing the durability of structures. Promising research areas include improving the durability of ecological materials, optimizing their composition using local raw materials and industrial waste, and creating new self-repairing composites, opening up opportunities for sustainable industrial construction. The results also highlight the need for new life cycle assessment methods for environmental materials, considering not only economic factors but also long-term environmental impacts, enabling more accurate evaluation of their environmental footprint and informed decisions in industrial construction.

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Serhii Pavlovskyi — PhD in Technical Sciences, Associate Professor, O.M. Beketov National University of Urban Economy in Kharkiv, 61002, 17 Marshal Bazhanov Str., Kharkiv, Ukraine https://orcid.org/0000-0002-9891-2133.

Roman Tkachenko —PhD in Technical Sciences, Associate Professor, O.M. Beketov National University of Urban Economy in Kharkiv, 61002, 17 Marshal Bazhanov Str., Kharkiv, Ukraine https://orcid.org/0000-0003-3899-1826.

Serhii Romanenko — Senior Lecturer, O.M. Beketov National University of Urban Economy in Kharkiv, 61002, 17 Marshal Bazhanov Str., Kharkiv, Ukraine, https://orcid.org/0009-0005-8811-3070.

Krystyna Borshchevska — Student, O.M. Beketov National University of Urban Economy in Kharkiv, 61002, 17 Marshal Bazhanov Str., Kharkiv, Ukraine, https://orcid.org/0009-0000-6998-8916.

Serhii Alforov — Postgraduate Student, O.M. Beketov National University of Urban Economy in Kharkiv, 61002, 17 Marshal Bazhanov Str., Kharkiv, Ukraine, https://orcid.org/0000-0003-3451-1004.

Сергій Павловський
Роман Ткаченко
Сергій Романенко
Кристина Борщевська
Сергій Алфьоров

ІННОВАЦІЙНІ ПІДХОДИ ДО БУДІВНИЦТВА З ВИКОРИСТАННЯМ ЕКОЛОГІЧНИХ МАТЕРІАЛІВ ДЛЯ ПОБУДОВИ ОБ'ЄКТІВ ВИРОБНИЧОЇ ІНФРАСТРУКТУРИ

Харківський національний університет міського господарства імені О.М. Бекетова

У статті представлено результати експериментального дослідження застосування екологічних матеріалів для будівництва об'єктів виробничої інфраструктури, проведеного впродовж 2022-2024 років. На основі серії стандартизованих випробувань здійснено порівняльний аналіз фізико-механічних характеристик традиційних та екологічних матеріалів (сталь/перероблена сталь, звичайний/геополімерний бетон, мінеральна вата/костра льону та конопель, керамічна плитка/бамбукові панелі). Встановлено, що екологічні матеріали досягають 85-95 % міцнісних показників традиційних аналогів при зменшенні ваги конструкцій на 30-40 %. Підтверджено зниження енергоспоживання будівель на 25-35 % та скорочення викидів CO_2 при виробництві на 40-60 %. Дослідження фізико-механічних властивостей виявило, що перероблена сталь демонструє зниження міцності на розтяг лише на 5-8 % при зменшенні ваги конструкцій на 3%, а геополімерний бетон показує зниження міцності на стиск на 10 % порівняно з бетоном. Теплоізоляційні матеріали на основі костри льону та конопель продемонстрували підвищення теплопровідності на 10% при значному зниженні щільності на 60 %. Випробування на довговічність показали зниження морозостійкості на 25 % та вогнестійкості на 20-25 %, що вимагає розробки додаткових технічних рішень. Техніко-економічний аналіз життєвого циклу продемонстрував, що незважаючи на вищу початкову вартість екологічних матеріалів на 15-20 %, їх застосування забезпечує зниження експлуатаційних витрат на 30-40 %. Найбільш суттєвим є скорочення витрат на опалення та охолодження на 35-40%. Підтверджено можливість повторної переробки 85-90 % матеріалів, що знижує витрати на утилізацію на 50-60 %. За результатами прискорених випробувань на старіння встановлено, що термін експлуатації конструкцій з екологічних матеріалів досягає 20-25 років при збереженні основних експлуатаційних характеристик. Виявлено підвищену стійкість геополімерних бетонів до агресивних середовищ – збереження до 90 % міцності після тривалого впливу хімічно активних речовин. Розроблено практичні рекомендації щодо вибору та застосування екологічних матеріалів з урахуванням специфіки експлуатації промислових об'єктів та запропоновано методику комплексної оцінки їх ефективності

Ключові слова: сталий розвиток; енергоефективність; життєвий цикл; техніко-економічний аналіз; фізико-механічні властивості

Сергій Павловський — к.т.н., доцент, Харківський національний університет міського господарства імені О.М. Бекетова, 61002, вул. Маршала Бажанова, 17, м. Харків, Україна, https://orcid.org/0000-0002-9891-2133.

Роман Ткаченко — кандидат технічних наук, доцент, Харківський національний університет міського господарства імені О.М. Бекетова, 61002, вул. Маршала Бажанова, 17, м. Харків, Україна, https://orcid.org/0000-0003-3899-1826.

Сергій Романенко — старший викладач, Харківський національний університет міського господарства імені О.М. Бекетова, 61002, вул. Маршала Бажанова, 17, м. Харків, Україна https://orcid.org/0009-0005-8811-3070.

Кристина Борщевська — студентка, Харківський національний університет міського господарства імені О.М. Бекетова, 61002, вул. Маршала Бажанова, 17, м. Харків, Україна https://orcid.org/0009-0000-6998-8916.

Сергій Алфьоров — аспірант, Харківський національний університет міського господарства імені О.М. Бекетова, 61002, вул. Маршала Бажанова, 17, м. Харків, Україна https://orcid.org/0000-0003-3451-1004.