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INNOVATIVE MATERIALS IN CONSTRUCTION: SUSTAINABILITY, STRENGTH AND ENERGY EFFICIENCY

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Abstract
The article presents an overview of modern innovative materials used in the construction industry, with an emphasis on their properties that contribute to sustainable development, as well as their strength and energy efficiency characteristics. A classification of the materials under consideration is proposed, including geopolymer concretes, nanostructured composites, phase-change materials, aerogels and biomaterials. Particular attention is paid to the role of these materials in the formation of a sustainable architectural environment capable of adapting to modern environmental and energy challenges. An analysis of strength and thermal insulation indicators is carried out, comparative characteristics of various materials are presented and prospects for the use of innovative solutions in energy-efficient construction are revealed. This study is based on current scientific publications, international standards and experience in implementing sustainable design projects.

Keywords: Innovative materials, sustainable construction, strength, energy efficiency, thermal regulation, geopolymers, nanoconcrete, phase-change materials, construction technologies, environmental friendliness.

Introduction

The scientific novelty of the article lies in the comprehensive study of innovative building materials in terms of their contribution to sustainable development, increasing the strength of structures and ensuring energy efficiency. This approach allows us to identify the synergistic effect of these materials on the formation of a modern architectural environment. Unlike most studies that consider these aspects in isolation, this paper proposes a classification of materials by functional feature (structural, thermal insulation, adaptive, bio-oriented) and conducts a system analysis of their characteristics. Particular attention is paid to materials with integrated properties that simultaneously provide high mechanical strength and reduced thermal conductivity. In addition, the article summarizes international experience in the application of innovative technologies in sustainable construction, taking into account LEED, BREEAM and DGNB standards, which expands the possibilities of practical application of the presented solutions. Thus, the study contributes to the development of scientific understanding of the possibilities of using innovative materials in the context of sustainable development and greening of the construction industry.

The modern construction industry is characterized by increasing demands for environmental sustainability, energy efficiency and economic efficiency of constructed objects. Traditional building materials such as concrete, brick and wood are being re-evaluated in the context of their ability to meet these criteria. This paper analyzes the key characteristics and advantages of innovative building materials that represent an alternative to traditional solutions, as well as studies the prospects for their widespread implementation in construction practice. The potential opportunities, limitations and factors that facilitate or hinder the transition to the use of new materials in mass construction are considered. Innovative building materials are a heterogeneous group of substances and composites developed using advanced technologies and fundamental scientific achievements. The purpose of developing these materials is to optimize the performance characteristics of buildings and structures. They play a decisive role in the implementation of the concept of sustainable development, improving energy efficiency and increasing the service life of construction projects [1]. Classification of innovative materials can be carried out according to a number of key features, including origin, technological features of production, functional purpose and compliance with environmental safety criteria. A systematic classification of innovative building materials is presented in Table 1.

Table 1 - Classification of innovative building materials

№	Material type	Description and characteristics	Examples of materials	Main advantages
1	**Eco-materials**	Uses recycled waste and renewable resources, reducing carbon footprint	Geopolymer concrete, concrete with additives of ash, broken glass, plastic	Waste management, reduction of CO_2 emissions
2	**Nanostructured materials**	Contain nanoparticles that improve the structure and properties of materials	Nano concrete, nano coatings based on TiO_2	Increased strength, water resistance and self-cleaning
3	**Intelligent (smart) materials**	Change properties depending on temperature, voltage, humidity	Self-healing concrete, thermochromic/electrochromic glass	Restoration of microcracks, energy saving
4	**Biomaterials**	Formed with the participation of biological agents or from organic raw materials	Biocement (bacteria based), mycelial blocks	Eco-friendly, biodegradable, adaptable
5	**Phase change materials (PCM)**	Accumulate and release thermal energy during phase transitions	Paraffins, hydrated salts, PEG-based polymers	Improved thermoregulation, reduced energy consumption
6	**New generation composite materials**	Materials with reinforcement or multilayer structure	Carbon fibers, glass composites, polymer concrete	Durability, lightness, resistance to aggressive environments

Consequently, the category of innovative building materials covers a wide range of technological solutions aimed at comprehensive improvement of both functional characteristics and sustainability and energy efficiency indicators of building objects. The presented classification reflects the interdisciplinary nature of the approach to solving current problems facing the modern construction industry.

The concept of sustainability in the context of construction is a comprehensive approach aimed at minimizing the negative impact of buildings and related construction processes on the environment, along with ensuring economic feasibility and social well-being. In the context of global climate change, intensive urbanization and shortage of natural resources, sustainable construction is considered not as an optional direction, but as an imperative condition for the further development of the construction industry [2].

In accordance with the definition proposed by the World Green Building Council, a sustainable building is defined as "a structure that at the design, construction and operation stages is characterized by the most efficient use of resources, minimization of negative impact on the environment, as well as a positive effect on human health and comfort" [3].

The fundamental principles of sustainable construction include:

1. Rational use of natural resources. This principle involves reducing the consumption of water, energy resources and building materials, as well as the active use of renewable energy sources such as solar, wind and geothermal energy.
2. Minimizing waste generation. The emphasis is on recycling building materials, reducing carbon dioxide (CO_2) emissions and reducing environmental pollution.
3. Improving energy efficiency and thermal inertia. This aspect is implemented through the use of innovative insulation materials, modern façade systems and passive architectural solutions [4].
4. Optimizing the quality of life. It involves improving the indoor microclimate, ensuring optimal insolation and ventilation, as well as reducing noise pollution and the concentration of harmful substances in residential and public buildings [5].
5. Life Cycle Assessment (LCA). This approach takes into account all stages of the building’s life cycle, starting with the extraction of raw materials and ending with the disposal of the facility after completion of operation.

The use of innovative building materials is one of the determining factors in increasing the sustainability of buildings. In particular, the use of geopolymer concretes allows for a significant reduction in greenhouse gas emissions (by 40–80%) compared to traditional cement mortars. The introduction of phase change materials (PCM) into enclosing structures provides passive thermal regulation of interior spaces, reducing the need for air conditioning and heating systems. The use of nanomaterials helps to increase the durability of building elements, which in turn reduces the need for repair and reconstruction work.

In addition, one of the important areas of sustainable construction is the adaptation of buildings to changing climatic conditions. This requires the development of flexible design solutions, as well as the use of building materials that are highly heat-resistant, moisture-resistant and resistant to extreme weather conditions.

Sustainable construction standards are being actively implemented internationally, such as:

- LEED (Leadership in Energy and Environmental Design, USA);
- BREEAM (Building Research Establishment Environmental Assessment Method, UK);

- DGNB (Deutsche Gesellschaft für Nachhaltiges Bauen, German Sustainable Construction Standard);
- EDGE (Excellence in Design for Greater Efficiencies, IFC).

These certification systems allow for a comprehensive assessment of building sustainability based on multiple criteria, including energy efficiency, indoor environmental quality, and water management efficiency [6].

Thus, sustainability should be considered an integral component of a modern 21st century construction strategy. Integration of environmental, social, and economic aspects into architectural and technological solutions in construction allows for the creation of buildings that meet current challenges and the requirements of future generations.

The strength characteristics of building materials are decisive for their ability to withstand mechanical loads without deformation or destruction. In the context of modern engineering tasks, including high-rise construction, construction of bridge structures and operation in aggressive environments, the use of innovative materials characterized by increased strength, crack resistance and durability is of particular importance. One of the promising areas is the use of geopolymer concretes, which are materials obtained through alkaline activation of aluminosilicate compounds. These materials demonstrate compressive strength in the range of 60-100 MPa after 24 hours of hardening, which is comparable to or exceeds the indicators typical of traditional Portland cement concrete. Ultra-High Performance Concrete (UHPC), reinforced with metal or glass fibers, is characterized by compressive strength exceeding 150 MPa and tensile strength up to 15 MPa, as well as increased resistance to aggressive environments and cyclic freeze-thaw processes. Due to its properties, UHPC is used in the construction of bridges, tunnels and other structures subject to high loads. Modern composite materials, such as carbon fiber-reinforced polymers (FRP) and fiberglass, have high strength at a relatively low weight. For example, carbon fibers demonstrate a tensile strength exceeding 3.5 GPa and an elastic modulus reaching 230 GPa. Nanoconcretes modified with titanium dioxide nanoparticles, carbon nanotubes or graphene are characterized by improved adhesion between the cement matrix and the filler, which leads to an increase in compressive strength by 20-50% compared to conventional compositions. In addition, there is an increase in resistance to microcracks and improved moisture resistance. Self-healing concrete containing microcapsules with reagents or biobacteria (for example, Bacillus subtilis) is able to independently eliminate cracks up to 0.5 mm wide, restoring the tightness and monolithicity of the structure. This can significantly increase the service life of the material without additional costs for repair and maintenance. New types of biocements and clay-organic composites (based on microalgae, fermenting bacteria, mycelium and other biological components) demonstrate lower strength indicators at the initial stages (10-25 MPa), but have the ability to self-heal and strengthen the structure over time. These materials are considered promising for use in low-rise and temporary construction.

In general, innovative building materials demonstrate significantly superior strength characteristics compared to traditional building compositions. It is necessary to take into account not only compressive strength, but also tensile strength, resistance to crack propagation, the ability to self-heal the structure and adaptation to various operating conditions. To conduct a comparative analysis of the key strength parameters of various types of innovative building materials, as well as their features and advantages in construction practice, a corresponding table is presented.

Table 2 - Comparative table of strength characteristics of innovative materials

Material	Compressive strength (MPa)	Tensile strength (MPa)	Features and benefits
Geopolymer concrete	60-100	6-10	Resistant to high temperatures, environmentally friendly
Ultra-high-performance concrete (UHPC)	150-200	10-15	High crack resistance, frost resistance
Nano concrete	80-120	7-12	Extended service life, low porosity
Carbon fiber composite	>3500 (on the break)	-	High strength to weight ratio
Self-healing concrete	30-60	4-8	Automatic restoration of microcracks
Biomaterials on mycelium based	10-25	1-3	Lightweight, biodegradable, environmentally friendly

It should be noted that innovative building materials not only improve the strength characteristics of building structures, but also expand their functionality. The introduction of these materials contributes to more efficient use of resources, reduced repair and maintenance costs, and increased safety of buildings in the long term.
Energy efficiency in construction is defined as the ability of a building to minimize energy consumption while providing comfortable living or working conditions. One of the key areas for improving energy efficiency is the use of innovative materials that help reduce heat loss, provide effective thermoregulation, and optimize the indoor microclimate.
According to data presented in a study by the International Energy Agency (IEA), buildings consume about 30% of the total energy produced in the world, a significant share of which is accounted for by heating, ventilation, and air conditioning (HVAC) systems [7]. This fact necessitates the integration of energy-efficient solutions both at the design stage of buildings and when choosing the building materials used.
Modern high-tech thermal insulation materials can significantly reduce heat loss without increasing the thickness of enclosing structures. These include:
1. Aerogels. These materials are among the most effective heat insulators, characterized by thermal conductivity in the range of 0.012–0.018 W/m•K, which is almost two times lower

than that of traditional polystyrene foam. Aerogels are used in thermal insulation of facades, roofs and utility lines.

2. Vacuum Insulation Panels (VIP). VIP panels with thermal conductivity of less than 0.008 W/m•K allow achieving high heat transfer resistance with minimal thickness (up to 2 cm).

Phase change materials (PCM) are a promising area in the field of passive thermal regulation of buildings. They accumulate excess thermal energy during the phase transition from a solid to a liquid state and release it during the reverse process. This helps smooth out temperature fluctuations during the day and reduce the load on heating and cooling systems. For example, adding paraffins to gypsum board panels or plaster mixes can reduce the indoor temperature by 2–4°C in the summer, which is equivalent to saving up to 15% of the electricity spent on air conditioning [8].

Energy efficiency of facades and glazing plays an important role in conserving thermal energy. The key innovations in this area are:

1. Chromogenic (electrochromic, thermochromic) glass. This glass can automatically regulate light transmission and heat gain depending on the outside temperature or intensity of solar radiation [7].
2. Heat-reflecting coatings and high-emissivity films. These solutions are aimed at reducing heat loss through glazing at night.
3. Thermoactive facades. These structures, combining layers with different thermal conductivity and PCM, ensure the adaptation of enclosing structures to seasonal changes in climatic conditions.

Modern energy-saving building systems based on the use of porous concrete, foam glass, hempcrete or straw panels combine thermal insulation and structural properties. For example, the thermal conductivity of hempcrete is 0.05–0.07 W/m•K while ensuring good vapor permeability and environmental safety [9]. The use of such solutions is especially effective in the context of energy-independent and low-rise construction.

Despite the obvious advantages, the widespread introduction of innovative building materials into construction practice is constrained by a number of factors, including: higher cost compared to traditional materials; insufficiently developed regulatory framework and lack of generally accepted standards; limited awareness of developers and designers about the properties and advantages of these materials [10].

Innovative building materials open up new opportunities for the development of sustainable and energy-efficient construction. The key areas that determine the future of the industry are increasing strength characteristics, reducing the negative impact on the environment and improving the thermal insulation properties of building structures. For the successful implementation of innovations, active interaction between the scientific community, business representatives and government institutions is necessary, aimed at developing standards, improving the qualifications of specialists and stimulating the development and implementation of new technologies.

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