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СУЧАСНЕ БУДІВНИЦТВО ТА АРХІТЕКТУРА

ЗБІРНИК НАУКОВИХ ПРАЦЬ

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БУДІВЕЛЬНІ КОНСТРУКЦІЇ

БУДІВЕЛЬНІ МАТЕРІАЛИ ТА ТЕХНОЛОГІЇ

ІНЖЕНЕРНІ МЕРЕЖІ ТА ОБЛАДНАННЯ

ТЕХНОЛОГІЯ ТА ОРГАНІЗАЦІЯ БУДІВЕЛЬНОГО ВИРОБНИЦТВА

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BIONICS AS THE FOUNDATION OF SUSTAINABLE DEVELOPMENT IN CONTEMPORARY ARCHITECTURE: ENERGY EFFICIENCY AND SYNERGY WITH THE ENVIRONMENT

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Abstract. The article explores bionics as a scientific and methodological foundation for creating sustainable architecture capable of energy-efficient functioning and achieving synergy with the natural environment. It examines the evolution of bionics from the formal imitation of organic forms to the comprehensive application of biomimetic principles. Through specific examples – such as the passive ventilation system of the Eastgate Centre in Zimbabwe, inspired by termite mound architecture, and façade concepts that mimic photosynthesis – the article reveals mechanisms for implementing bionic design solutions. Particular attention is given to analyzing the energy efficiency, adaptability, and resource-saving characteristics of bio-inspired architectural objects.

The study highlights the contemporary understanding of bionics, which focuses on the principles of cyclicality, adaptability, and zero-waste design derived from natural ecosystems. It provides a detailed analysis of examples ranging from passive ventilation and thermal regulation systems modeled after termite mounds to adaptive façade systems that imitate photosynthesis and plant regulatory mechanisms. Special attention is paid to environmental synergy achieved through efficient resource management – for instance, mimicking water-harvesting strategies of desert insects or adopting lightweight yet durable structural analogues inspired by biological prototypes such as bone or spider silk to minimize material consumption.

The discussion systematizes the advantages of the bionic approach – including enhanced energy efficiency, reduced operational costs, and improved comfort – while also addressing the challenges of its implementation, such as high research costs and the need for interdisciplinary collaboration. The article substantiates the idea that bionics serves not only as a tool for solving engineering problems but also as a catalyst for shaping a new architectural philosophy aimed at fostering harmony between the built and natural environments.

The practical significance of the study lies in its potential use by researchers, educators, graduate students, and practitioners engaged in related scientific and design inquiries.

Keywords: bionics, architecture, energy efficiency, environment.

Introduction. In the context of global climate change and the depletion of natural resources, the issue of energy efficiency and the ecological integration of architecture has become increasingly relevant. Traditional construction practices, which operate as energy-intensive systems that often oppose the natural environment, are progressively demonstrating their inadequacy in addressing contemporary challenges.

The modern construction industry is among the largest consumers of natural resources and a major source of greenhouse gas emissions. Traditional architecture, shaped during an era of abundant energy resources, largely functions according to the principles of a "closed system". It resists climatic conditions, relying on active engineering systems – heating, ventilation, and air conditioning – to maintain interior comfort. This approach inevitably results in high energy consumption, places excessive pressure on ecosystems, and further deepens the divide between the artificial built environment and the natural world.

Such an energy-intensive paradigm, which treats a building as an object isolated from its contextual environment, proves increasingly vulnerable to global challenges such as climate change, resource scarcity, and urban crises. This situation highlights the urgent need for a radical reassessment of design principles and for the creation of architecture that does not confront nature but instead becomes integrated into natural cycles while minimizing its ecological footprint.

Contemporary architecture faces the global imperative of transitioning toward sustainable development principles, which require a drastic reduction in energy consumption and the minimization of environmental impact. In this context, the bionic (biomimetic) approach is no longer merely an aesthetic choice but becomes an effective tool for addressing practical design and environmental challenges.

Analysis of Recent Research and Publications. The issue of the bionic (biomimetic) approach in architecture has gained significant prominence in recent years, as humanity has become increasingly aware of the importance of minimizing environmental impact.

In the article by X. Wang, L. Xiao, L. Fan, N. A. Mokhtar, and M. K. Azhar Mat Sulaiman, the authors examine bionic architecture through a review of 109 studies published between 2010 and 2024. They propose a classification of biomimetic solutions, dividing them into three categories: façade systems, structural optimization, and energy-generating envelopes. The authors demonstrate the potential of transferring biological principles from living systems into architectural strategies and provide practical recommendations for architects and engineers [1].

In the article "Biomimicry in Architecture: A Review of Definitions, Case Studies, and Design Methods", the authors analyze the transition from simple imitation of natural forms to the development of complex system-oriented approaches. This publication is particularly useful for classifying different levels of biomimicry (form, process, ecosystem) [2].

A. M. A. Faragalla and S. Asadi, in their study "Biomimetic Design for Adaptive Building Façades: A Paradigm Shift towards Environmentally Conscious Architecture", investigate biomimicry as a foundation for designing façades that dynamically respond to environmental conditions. The article focuses on biomimetic methods developed for adaptive façade design and evaluates their effectiveness in comparison with other approaches. The authors conducted a comprehensive literature review and examined early-stage design strategies for such building envelopes [3].

The application of bionic principles in architecture and design has also been explored within the Ukrainian academic context, although it has not yet received as widespread implementation as in international practice. Various aspects of bionic approaches have been studied by researchers such as O. Oliinyk, Yu. Chopyk [4], O. Orlova [5], among others.

Research Aim and Objectives. The aim of this study is to provide a theoretical justification and analysis of bionics as a scientific and methodological foundation for creating energy-efficient architecture capable of synergistic interaction with the environment in the context of sustainable development.

In line with this aim, the following research objectives have been formulated:

– to analyze the evolution of the bionic approach in architecture, tracing the transition from formal imitation to the replication of principles, processes, and systemic interactions;

– to identify and examine key principles of contemporary bionics that are most relevant to addressing sustainability challenges (energy efficiency, cyclicity, adaptability);

– to investigate and systematize concrete examples of successful implementation of bionic solutions in architectural practice;

– to systematize the advantages and identify the main challenges hindering the widespread adoption of the bionic approach in contemporary architectural design.

Research Methods. This study is based on an interdisciplinary methodological framework combining analytical and comparative approaches. The analytical method was used to investigate the theoretical foundations of bionics and its evolution within architectural discourse. Comparative analysis made it possible to identify key similarities and differences between natural systems and their architectural analogues, emphasizing the transfer of biological principles into design strategies.

Case studies of landmark buildings inspired by biological elements provided the empirical basis for evaluating the effectiveness of bionic solutions in enhancing energy efficiency and integrating environmentally derived systems. In addition, methods of systematization and synthesis were employed to generalize the findings and formulate conceptual conclusions. This integrative approach ensured a comprehensive understanding of bionics both as a scientific discipline and as a practical design paradigm that contributes to the sustainable development of architecture.

Research Results. Today, bionics is not merely a stylistic approach but a conceptual framework that enables the transition to a new architectural paradigm – one in which a building functions as a living system in unity with its surrounding ecosystem. Let us examine how the adoption of structural, functional, and energetic principles of living nature can form the foundation for synergistic architecture that interacts effectively with the environment rather than opposing it.

Historically, the interaction between architecture and nature has taken various forms. The initial stage – commonly referred to as biomorphism or formal imitation – dates back to ancient times (e.g., classical orders inspired by plant motifs) and found vivid expression in the Art Nouveau era as well as in the works of notable twentieth-century architects such as Antonio Gaudí and Frank Lloyd Wright [6]. At this stage, the primary focus was on borrowing external, visual, and aesthetic characteristics of natural objects. Buildings could resemble a flower, a shell, or a skeletal structure, yet their functional and engineering essence remained anthropogenic and often energy-intensive.

The essence of contemporary bionics (or biomimicry – a term popularized by Janine Benyus [7]) lies in a fundamental shift in focus: from visually copying natural forms to imitating natural principles, processes, and systems. This approach views nature not as a source of aesthetic references but as a highly sophisticated laboratory that, through millions of years of evolution, has arrived at the most efficient and resource-conserving solutions. Modern bionics in architecture is an interdisciplinary process that integrates biology, engineering, materials science, and design to develop solutions that are both innovative and deeply adapted to environmental conditions.

The analysis of natural systems allows us to identify several fundamental principles that directly correspond to the goals of sustainable development and are critically important for designing energy-efficient architecture.

Energy efficiency and the use of environmental conditions. Living systems operate using available energy (primarily solar) and adapt to local climatic conditions. They rely on passive mechanisms for thermoregulation, lighting, and ventilation. In architecture, this translates into the prioritization of passive design, the optimization of building form for interaction with solar radiation and wind flows, as well as the use of geothermal energy and natural lighting.

Zero-waste operation and cyclicality. In ecosystems, the concept of "waste" does not exist – waste from one organism becomes a resource for another. The principle "waste = food" is the foundation of biological metabolism. For architecture, this means a transition toward the principles of the circular economy: designing buildings as materials banks, using biodegradable or fully renewable materials, and integrating closed-loop systems for water and nutrient cycles (e.g., water purification systems, integrated green infrastructure).

Adaptability and responsiveness. Nature does not produce static or monolithic solutions. Living organisms constantly respond to environmental changes in real time – leaves orient themselves toward the sun, stomata open for gas exchange, animals' fur adjusts its density. In architecture, this translates into kinetic and adaptive façades capable of altering their configuration, transparency, or thermal conductivity in response to weather conditions, time of day, or user needs, thus optimizing microclimate and energy consumption.

The theoretical principles of bionics find practical embodiment in concrete architectural and engineering solutions that enable a radical reduction in building energy consumption and significantly improve the quality of the indoor environment.

One of the most widely cited and recognized examples of the successful implementation of a bionic principle at the scale of an entire building is the Eastgate Centre in Harare, Zimbabwe (architect Mick Pearce, 1996) [8]. The architectural task involved creating a large office complex in a hot climate without relying on expensive and energy-intensive air-conditioning systems. The architect turned to an analysis of the mounds built by the African termite species Macrotermes michaelseni. These termites are able to maintain a stable internal temperature (approximately 30–31 °C) within their nests, enabling the cultivation of fungal gardens, despite the significant fluctuations in outside temperature, which range from 3 °C at night to 42 °C during the day. They achieve this through a sophisticated system of ventilation channels and the use of stack effect. Warm air generated inside the mound rises and exits through an opening, creating a pressure differential that draws cooler air in through the porous lower sections of the structure. At night, the cool outside air chills the massive walls of the termite mound.

Mick Pearce employed this principle in the design of the Eastgate Centre as follows:

Passive ventilation. The building consists of two blocks separated by an atrium covered with a glass roof. Ventilation operates through natural stack effect. Fans (which consume significantly less energy than air-conditioning compressors) draw in cool night air from outside.

Thermal mass. Air circulates through cavities in the concrete floor slabs, cooling the building's massive structure (similar to the role of soil mass in a termite mound).

Daytime cycle. During the day, the ventilation system is largely switched off. The concrete mass, cooled overnight gradually absorbs heat generated by occupants, lighting, and office equipment, maintaining a comfortable indoor temperature (23–25 °C). Warm air from the offices rises and exits through exhaust shafts on the roof, creating a draft that promotes the inflow of fresh, cooler air from below.

As a result of this bionic strategy, the Eastgate Centre consumes less than 10 % of the energy that would be required for a conventional building of similar size equipped with full air-conditioning in a comparable climate [9]. This example clearly demonstrates the economic and environmental effectiveness of bionics.

While the Eastgate Centre illustrates the imitation of a natural system, adaptive façades represent the imitation of processes and reactions characteristic of living organisms. An innovative direction involves integrating living biological processes directly into the building envelope. A striking example is the BIQ Building (Hamburg, Germany, 2013) [10]. The façade of this building consists of glass panels that function as photobioreactors. Within these panels, microalgae are cultivated in a nutrient-enriched aqueous solution. The system performs several functions simultaneously:

Adaptive shading. In sunny weather, the algae grow actively (photosynthesize), making the suspension denser and greener, which effectively shades the interior spaces and prevents overheating.

Energy production (biomass). The algae are periodically harvested, and the resulting biomass is used in a cogeneration unit to produce biogas (methane), which supplies the building with heat and electricity.

Thermal energy. The water inside the panels is heated by the sun. This heat is captured by heat exchangers and used for space heating and domestic hot water.

Thus, the façade transforms from a passive envelope into an active, metabolic element that generates resources and adapts to external conditions, much like a plant leaf.

Other approaches to adaptation involve creating systems that respond to environmental changes without energy input, relying instead on the intrinsic properties of materials.

One such mechanism is the "pinecone principle" (hygroscopicity). Pinecones open their scales in dry weather (to release seeds) and close them in humid conditions. This movement occurs passively due to the differing fiber structures in the two layers of each scale, which expand differently when absorbing moisture (the hygroscopic effect). In architecture, this principle is applied in hygromorphic envelopes. For example, the research pavilions of the ICD/ITKE at the University of Stuttgart feature façades made from composite wooden panels. These elements are engineered so that they change their curvature (opening or closing) solely in response to variations in relative humidity, thereby regulating ventilation and daylight without any sensors, motors, or power sources [11].

Another biomimetic strategy is the "porous leaf principle". Microscopic pores on a leaf's surface open and close to regulate gas exchange depending on light levels and humidity. This concept

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has also been translated into architecture and has inspired the development of mechanical kinetic façades. The most well-known example is the Al Bahar Towers in Abu Dhabi. Their façade consists of thousands of individual modules. These "umbrellas" automatically open and close throughout the day in response to the sun's movement. They block direct solar radiation while allowing diffuse light to enter, which, according to calculations, reduces heat gain by more than 50%, significantly decreasing the need for air-conditioning [12]. It should be noted that this system is mechanized (unlike the passive "pinecone principle" described above), yet it directly emulates the biological strategy of adapting to extreme conditions through dynamic changes in form.

The examples presented illustrate how the shift from merely copying natural forms to imitating natural processes and systems enables the creation of architecture that enters into a synergistic, productive interaction with the environment – an essential principle of sustainable development.

Examining how bionic principles optimize the use of other key resources – namely water and materials, and how they support the creation of closed-loop systems, several factors can be identified. In the context of global freshwater scarcity, architecture must transition from simply consuming water resources to actively harvesting and managing them efficiently. Nature offers unique strategies for survival in extremely arid environments.

A classical example is the Namib Desert beetle (Stenocara gracilipes). This insect is capable of collecting drinking water from fog carried inland by ocean winds. Its elytra possess a unique microstructure: hydrophilic bumps alternate with flat hydrophobic channels coated with a wax-like substance [13]. Moisture from the fog condenses on the hydrophilic peaks, forming microscopic droplets. Once a droplet reaches a critical size, it detaches and, landing on the hydrophobic surface, easily rolls along the channels directly toward the beetle's mouthparts.

This mechanism has inspired the development of fog-harvesting systems. While similar systems existed earlier, the bionic approach makes it possible to optimize their performance by creating surfaces with controlled hydrophilic and hydrophobic structures. In addition, façade panels and roofing materials capable of passively collecting atmospheric moisture (condensation, fog, dew) and directing it into a building's rainwater harvesting system are being developed. The principle can also be integrated into supply-air systems for passive dehumidification or humidification, reducing the energy required for air treatment. Such technologies have the potential to enable autonomous water-supply systems in arid and coastal regions.

The principle of "doing more with less" is fundamental to biomimicry. Nature does not rely on excessive material; instead, it optimizes form and structure to achieve maximum efficiency with minimal expenditure of energy and matter.

For example, the internal structure of bones – particularly trabecular, or spongy, bone – is not solid. Its latticed configuration corresponds precisely to the lines of load and stress acting upon the bone, a principle known as Wolff's law. Material is present only where it is structurally necessary.

Another example is spider silk. In terms of specific strength, it can surpass steel while remaining exceptionally lightweight and flexible. This performance arises from the complex hierarchical arrangement of its protein molecules [14].

Plant structures such as leaf morphology (e.g., the ribbed structure of the Victoria amazonica water lily) or the form of tree trunks are likewise optimized to provide stiffness and resistance to wind loads.

Modern computational modeling techniques allow architects and engineers to adopt this biological approach to design. In such processes, the software grows the structure by adding material only where it is required to carry loads, while removing it from areas where it is unnecessary. The resulting components are lightweight, filigree-like elements that can save 40–60% of material compared to conventional beams or columns.

The architectural work of Frei Otto serves as a classic example of bionics. His design for the roof of the Munich Olympic Stadium is a materially efficient tensile structure whose form is dictated solely by the forces of tension.

Additive manufacturing technologies (3D printing) in construction make it possible to realize complex, optimized geometries that would be impossible – or prohibitively expensive – to produce using traditional methods. This opens the door to directly replicating efficient natural structures. Minimizing the use of primary materials, creating lighter structures (which reduces foundation loads and transportation costs), and the potential application of biopolymers for 3D printing are all steps toward a zero-waste, closed-loop construction paradigm.

Thus, analyzing evolution, principles, and concrete examples of bionic architecture makes it possible to systematize its advantages and identify the key challenges that hinder its widespread implementation.

The implementation of a bionic approach offers a range of multifaceted advantages that extend far beyond purely aesthetic or engineering considerations, including:

1. Energy efficiency and reduced operational costs. The example of the Eastgate Centre demonstrates that passive bionic thermoregulation systems can significantly (up to 90%) reduce energy consumption for heating, ventilation, and air-conditioning – typically the largest component of a building’s operating expenditures.

2. Enhanced comfort and indoor environmental quality. Passive ventilation systems ensure a continuous supply of fresh air, while adaptive façades optimize natural daylight. Together, these features create a healthy and productive indoor microclimate for occupants.

3. Resource efficiency. Structural optimization based on bionic principles substantially reduces material intensity in construction – and consequently, the energy required for raw material extraction, manufacturing, and transportation.

4. Resilience and adaptability. Buildings capable of passively responding to climatic shifts (such as hygroscopic pavilions) or autonomously harvesting water are less vulnerable to energy crises or disruptions in centralized infrastructure networks.

Despite these evident benefits, the widespread adoption of bionics faces several notable challenges:

High cost of research and innovation. Bionic solutions require extensive preliminary research, computational modeling, prototyping, and testing (as in the Al Bahar façade or the BIQ bioreactors). This increases initial project costs, which may deter investors who are not prepared to evaluate full life-cycle benefits or long-term savings.

Need for deep interdisciplinary collaboration. Effective bionic design cannot be achieved within traditional linear project structures. It requires close cooperation among architects, biologists, materials scientists, engineers, and climatologists from the earliest design stages [15]. This poses organizational and communication challenges for the construction industry.

Issues of scaling and standardization. Many innovative solutions remain at the level of experimental prototypes. Transforming them into standardized, certified, and economically viable construction products remains a complex technological and market challenge.

Regulatory constraints. Building codes are inherently conservative and typically focus on established materials and systems. The integration of dynamic and adaptive mechanisms requires the development of new standards and evaluation methods to ensure reliability and safety.

Thus, bionics offers a shift from the industrial paradigm of opposing nature toward a paradigm of learning from nature and integrating its most efficient solutions. The future potential lies in moving from the imitation of isolated biological principles to the emulation of entire ecosystems.

The architecture of the future will employ "living" materials (e.g., mycelium-based insulation, self-healing bacterial concrete); function as a metabolic system integrated into urban cycles (purifying air, managing stormwater, sequestering carbon); and generate more clean energy and water than it consumes [16].

Conclusions. Contemporary bionics has progressed from formal imitation (biomorphism) to the deep adoption of principles, processes, and interconnections characteristic of entire ecosystems. This transition is precisely what makes it relevant for addressing the complex challenges of today.

The principles of natural energy efficiency (passive strategies), cyclicality, and adaptability (response to environmental changes) form the foundation for implementing sustainable development in construction. The analysis of examples such as the Eastgate Centre (passive termite-mound thermoregulation), the BIQ Building (façade bioreactors), the Al Bahar Towers (kinetic shading), along with strategies for water harvesting and structural optimization, confirms the practical viability of bionic solutions. They make it possible to drastically reduce energy and resource consumption while simultaneously improving indoor environmental quality.

The main advantages lie in comprehensive optimization, reduced operational costs, and increased comfort. At the same time, significant barriers remain, including high initial costs, the need for deep interdisciplinary integration, and regulatory hurdles.

In summary, the bionic approach directly contributes to achieving key goals of sustainable development. Bionics extends beyond a purely engineering methodology; it forms a new architectural philosophy based on learning from, interacting with, and integrating natural models. It provides a pathway toward designing adaptive and efficient systems capable of genuine synergy between the built and natural environments.

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БІОНІКА ЯК ОСНОВА СТАЛОГО РОЗВИТКУ В СУЧАСНІЙ АРХІТЕКТУРІ: ЕНЕРГОЕФЕКТИВНІСТЬ ТА СИНЕРГІЯ З НАВКОЛИШНІМ СЕРЕДОВИЩЕМ

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Анотація. Стаття присвячена дослідженню біоніки як науково-методологічної основи для створення архітектури сталого розвитку, здатної до енергоефективного функціонування та синергії з навколишнім середовищем. У статті досліджується еволюція біоніки від формального наслідування органічних форм до комплексного застосування біоміметичних принципів. На конкретних прикладах, таких як система пасивної вентиляції будівлі Eastgate Centre у Зімбабве, запозичена з архітектури термітників, або концепції фасадів, які імітують фотосинтез, у статті розкриваються механізми реалізації біонічних рішень. Окрема увага приділена аналізу енергоефективності, адаптивності та ресурсозберігаючих якостей біоінспірованих об’єктів.

У статті також розглянуто сучасне розуміння біоніки, яке фокусується на принципах циклічності, адаптивності та безвідходності, які запозичені у природних екосистемах. У дослідженні детально проаналізовано конкретні приклади: від пасивних систем вентиляції та терморегуляції за прикладом термітників, до адаптивних фасадних систем, які імітують фотосинтез або механізми регуляції у рослин. Окрему увагу приділено синергії з довкіллям, яке можливе завдяки ефективному управлінню ресурсами. Зокрема, запозиченню механізмів збору води у пустельних комах та використанню легких та міцних структур за аналогією до біологічних прототипів (кістки, павутина) для мінімізації матеріалоємності.

У ході обговорення систематизовано переваги біонічного підходу (енергоефективність, зниження експлуатаційних витрат, підвищення комфорту) та проаналізовано виклики, які пов’язані з його впровадженням (такі як висока вартість досліджень, потреба у міждисциплінарній співпраці). У статті обґрунтовано, що біоніка виступає як інструмент для вирішення інженерних завдань, а також як драйвер формування нової архітектурної філософії, спрямованої на синергію між рукотворним середовищем та природним.

Практичне значення даного дослідження полягає в тому, що його матеріали можуть бути використані науковцями, дослідниками, викладачами, аспірантами та студентами у процесі наукових досліджень на суголосну тематику.

Ключові слова: біоніка, архітектура, енергоефективність, навколишнє середовище.

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RE-CREATION OF ARCHITECTURAL HERITAGE AS A SOURCE OF AUTHENTICITY

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Abstract. The problem of re-creation of architectural heritage has traditionally remained within the field of conflicting assessments. The classical doctrine established by the Venice Charter interpreted authenticity through the material substance of the monument; therefore, any re-creation was regarded as falsification. At the same time, historical experience shows that when not only the material fabric but also the very space of memory is lost, re-creation becomes the only means of restoring cultural continuity. At the turn of the 20th and 21st centuries, under the influence of the Nara Document, the Burra Charter, and the Riga Charter, the concept of authenticity expanded beyond material substance to include cultural, social, and semantic dimensions and, with this shift, the very understanding of re-creation also changed.

The purpose of the study is to substantiate re-creation as a cultural act capable of generating its own authenticity. The methodological framework combines instruments of architectural and conservation practice with interdisciplinary approaches. The use of historical-analytical, comparative, system-structural, and hermeneutic methods made it possible to consider re-creation not merely as a technical procedure but as a cultural act in which architecture becomes a carrier of memory and a medium of reflecting on the past.

As a result, a conceptual model of the multiplicity of authenticity was proposed (including material, functional, contextual, and conceptual dimensions), along with a typology of re-creation forms: scientific, representational, adaptive, imitative, and falsification. The article examines two polar forms – scientific and falsification – as examples of opposing strategies of interaction between authenticity and contemporaneity.

The study demonstrates that re-creation is not the antithesis of authenticity: it may serve as its source, creating conditions for renewed experience and interpretation of the past. In this process, the genuine and the imagined, memory and the re-created image continuously interact, forming a new, dynamic authenticity. An open question remains whether a falsified re-creation can, over time, become living heritage – accepted by society as its own.

Keywords: authenticity, architectural heritage, forms of re-creation, identity, falsification.

Introduction. The issue of re-creating architectural heritage has always generated divergent views. On the one hand, the classical understanding of authenticity required the highest degree of care for the original fabric of a monument – for those «traces of time» that convey historical truth. Within this framework, any re-creation of a lost structure was regarded as falsification, an attempt to construct the appearance of the real where it no longer existed. This approach is codified in the 1964 Venice Charter [1], which for decades defined the parameters of international restoration practice.

On the other hand, the experience of many countries demonstrates that the need for re-creation has repeatedly emerged – after wars, disasters, ideological prohibitions or simply through the passage of time. In some cases, this occurred even before the very notion of a «heritage monument» acquired its contemporary meaning; in others, it took place when protection systems failed. This raises a key question: does a re-created object continue the historical narrative, or does it already constitute a new version of it?

The late twentieth century marked a broadening of the concept of authenticity. The 1994 Nara Document on Authenticity [2], the 2000 Riga Charter [3] and the Burra Charter (1979–2013) [4] demonstrated that authenticity may be expressed not only through material substance but also through functions, traditions, techniques and collective memories and meanings. From this perspective, re-creation does not necessarily appear as a substitution of truth; it may operate as a means of restoring cultural memory and as a gesture of continuing historical dialogue.

The Ukrainian context is particularly illustrative. Here, the issue of re-creation carries a dual meaning: it is both a response to the immense losses of twentieth- and twenty-first-century architectural heritage, and an attempt to restore the spaces of memory that were destroyed together with material structures. In a setting of legal uncertainty and ongoing tension between the «copy» and the «monument», the cultural dimension of re-creation becomes decisive [5]. Ukrainian examples – from the reconstruction of historic urban centres to the recovery of lost religious buildings – demonstrate that re-creation increasingly extends beyond a technical operation and becomes a means of interpreting authenticity in a wider sociocultural sense.

Review of recent studies and publications. The problem of re-creating architectural heritage occupies an intermediate position between restoration theory, architectural practice and cultural studies. Several main directions can be distinguished in contemporary academic discourse, within which this issue is being developed.

Theoretical and doctrinal direction. This group of studies is concerned with interpreting the principles of authenticity and the permissibility of reconstruction within ICOMOS and UNESCO international documents, as well as post-conflict recovery guidelines [6].

The problem of re-creation is examined through the debate between the classical school (J. Viollet-le-Duc, C. Brandi) [7] and contemporary approaches (S. Labadi, S. Muñoz Viñas) [8–10]. These works emphasise the shift from «physical preservation» to «value-based authenticity», which includes the social and communicative dimensions of a monument.

Cultural and social approach. Re-creation is understood as a form of collective memory, identity and symbolic representation of the past (P. Nora) [11].

National and regional studies. Another direction comprises works analysing the practice of re-creation in specific countries – particularly in the post-socialist context (S. Kulevičius) [12]. These studies show how re-creation is often used as an instrument of memory policy and national identity.

Ukrainian context. In Ukrainian research (O. Plamenytska, O. Chahovets, K. Cherkasova and others), the topic of re-creation is examined within restoration methodology, regulatory frameworks and contemporary challenges of heritage protection [13–16]. The focus lies on the relationship between historical authenticity, legal constraints and the societal demand for recovering what has been lost.

Thus, the current state of research demonstrates a shift from interpreting re-creation as a «mistake» to understanding it as a cultural process that generates new types of authenticity.

The aim of this study is to articulate and substantiate the «concept of re-creation» in architectural heritage as a cultural act capable of generating its own modes of authenticity and shaping new layers of meaning within a monument.

Research tasks. To disclose the contradiction between re-creation as a «copy» and re-creation as a source of memory. To delineate the boundary between scientific re-creation and falsification. To identify the conditions under which re-creation can shift from a technical operation into a mechanism for reactivating authenticity.

Materials and methodology. The methodology is based on architectural restoration tools and interdisciplinary approaches. The study applies the historical-analytical method to trace the development of ideas about «re-creation» and authenticity in restoration practice; the comparative method to examine different forms of re-creation and their influence on the understanding of authenticity; systemic-structural analysis to identify the relationships between architectural material, symbolic meanings, and community memory; and a hermeneutic approach to interpret re-creation not only as a technical operation but also as a cultural act within contemporary restoration theory.

Research results. As a result of summarising the approaches presented in the works of A. Tomaszewski, S. Labadi, S. Muñoz Viñas, as well as in international ICOMOS documents, a conceptual model of the multiplicity of authenticity was proposed.

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The model synthesises four interrelated dimensions – material, functional, contextual and conceptual which together form an integrated field of authenticity of an architectural object. Each dimension has its own carriers: the material (original structures and historical construction techniques); the functional (the initial use and preservation of the object's operation); the contextual (the historical and cultural environment and visual connections); the conceptual (the author's intention, architectural idea and symbolic content) (Fig. 1).

Thus, authenticity appears not as a fixed property of matter, but as a dynamic system of interaction between different levels of meaning, which may be reactivated even in cases of complete material loss.

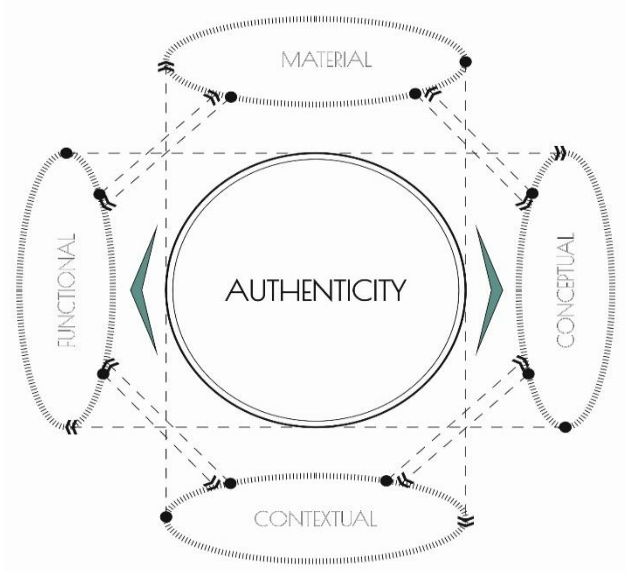

Fig. 1. The multiplicity of authenticity. Conceptual model. (Author)

Within this multidimensional model, re-creation emerges as a tool capable of activating different types of authenticity. Depending on its aims, methods and societal context, it may reinforce the material, functional, contextual or conceptual dimension. For this reason, contemporary practice demonstrates not a single but several forms of re-creation, which differ according to the source of authenticity that they reproduce.

The author's research made it possible to trace how the concept of «re-creation» functions within contemporary academic, professional and cultural discourses: from terminological and theoretical approaches to sociocultural and regulatory contexts. As a result, a typology of re-creation forms was developed, comprising five main forms (scientific, representational, adaptive, imitative and falsification), which differ in their relation to authenticity and in the ways, they activate it (Fig. 2). Each of them represents a specific way of actualising authenticity, yet none is an ideal or final model: all forms contain internal methodological and ethical conflicts – between accuracy and interpretation, memory and function, matter and meaning. These tensions define the contemporary field of discussion on re-creation as a cultural phenomenon.

This article examines two forms of re-creation: scientific and falsification as two polar models of interaction between authenticity and contemporaneity.

Scientific re-creation is based on reliable historical sources: drawings, archaeological research and photographic documentation and is aimed at restoring the original appearance of a monument as accurately as possible. Its key conflict lies in choosing between economic feasibility and the reliability of material authenticity: whether it is justified to use historical technologies, rare materials or manual craftsmanship when this significantly increases the cost of the work.

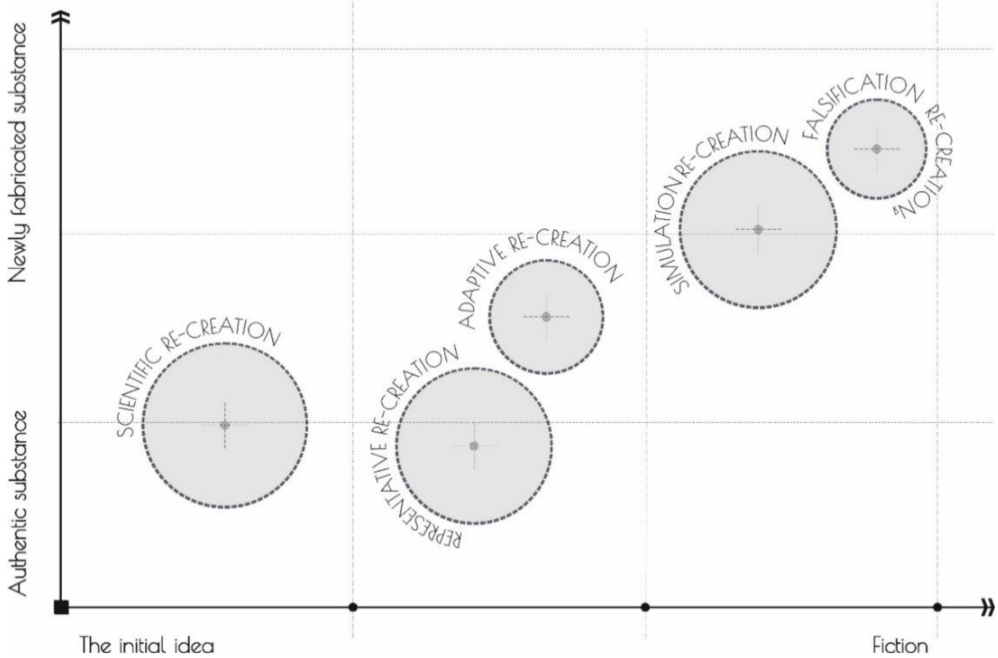

Fig. 2. Forms of re-creation. (Author)

The re-creation of the Ottoman bridge in Mostar, destroyed in 1993 during the Bosnian War, became one of the examples of scientific re-creation carried out under the auspices of UNESCO in 1997–2004 (Fig. 3). The reconstruction project was based on comprehensive archival and archaeological research, precise on-site recording of the surviving structural elements and an analysis of the hydrological conditions of the Neretva River. For the restoration of the arch, local Tenelija stone was used quarried from the same source as in the sixteenth century, along with the traditional technique of vaulting without reinforcement, using wooden centring. Each block of the bridge was crafted and numbered by hand, and the old fragments discovered during excavations were reintegrated into the structure [17].

Fig. 3. The Old Bridge in Mostar. Before destruction and after re-creation

The reconstruction of the bridge became not only a technical re-creation (reconstruction) but also a gesture of reconciliation, a restoration of trust between divided communities through the act of joint re-creation. In this case, authenticity appears not only in the material but also in the process, in which architecture becomes a means of cultural healing and a symbol of unity.

Falsification re-creation. This is the most radical form, creating the illusion of historical truth while in fact replacing it with a contemporary ideological or aesthetic interpretation. The conflict here lies between the modern perception of the past and its actual history. Such objects are presented as authentic but construct an «improved» or «convenient» past that corresponds to political or commercial agendas.

The Royal Palace in Vilnius (the Palace of the Grand Dukes of Lithuania) was the principal state residence of the Grand Duchy of Lithuania in the fifteenth–sixteenth centuries. In the nineteenth

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century, it was completely demolished by the Russian administration as part of the imperial policy of Russification. No vertical elements or structural parts of the palace survived – only archaeological remains of the foundations [18].

The re-creation carried out in 2002–2009 became a political and cultural project of independent Lithuania, a symbol of national dignity, the restoration of state continuity and cultural identity. The project was actively supported by the government and was perceived as an act of historical justice. At the same time, the building was constructed entirely from new materials, based on fragmentary archaeological data, reconstructive hypotheses and a national narrative, rather than on complete historical and architectural documentation. The palace was presented as «restored», without a clear public distinction between the new and the old. It was precisely this hypothetical character, together with the focus on visual recognisability and decorative persuasiveness, that created a situation in which imitative features merged with an ideological claim to authenticity.

In theoretical terms, this example demonstrates a falsification form of re-creation, in which re-creation executed without a sufficient source base acquires the status of historical truth, replacing scholarly verification with an emotional and political narrative (Fig. 4).

Fig. 4. Palace of the Grand Dukes of Lithuania. Image on an engraving and after re-creation

If in Mostar re-creation became an act of reconciliation, then in Vilnius it functions as an act of self-assertion. The restoration not so much of the historical object as of the image of statehood. Here, reconstruction does not transform into reconciliation, remaining a symbol of cultural revenge rather than a renewal of dialogue with the past.

The typology of re-creation forms (scientific, representational, adaptive, imitative and falsification) is an authorial development created within the framework of the dissertation research (2022–2025). The full version of the model constitutes part of the materials of the forthcoming defence. This article provides only brief definitions of the three additional forms that complement scientific and falsification re-creation.

Representational re-creation is based on the idea that the memory of an object may be conveyed not through literal replication but through an image. In this form, creative reinterpretation is allowed, provided that it «honestly» indicates the loss. Here, the intention to preserve memory prevails over material authenticity. A building or space may take on a new form while still performing the role of a symbol. This is no longer a copy of the past but rather a system of signs and markers that recall what has been lost.

This form of re-creation responds to the question: can society accept a new form as a representation of the past, even if it does not reproduce a specific historical building?

Adaptive re-creation arises when a historical object is brought back into contemporary life as a repurposed space that preserves only fragments of its historical appearance. The aim of such re-creation is to integrate the monument into the contemporary socio-economic and cultural context. As a result, the authenticity of the historical appearance may dissolve and give way to functional requirements (a museum, tourist centre, art space or administrative building).

The key question is whether such objects remain part of heritage if their present outweighs their past.

Adaptive re-creation does not deny history but shifts the focus. The monument retains only certain features of its past, while the new function gradually defines its appearance and mode of existence.

Imitative re-creation creates the «appearance of historicity». It is a stylisation of the past. The «architectural mask» reproduces recognisable elements of historical architecture but does not claim accuracy and does not refer to an actual heritage object. This form of re-creation operates with emotional «codes of memory»: stone, bastions, medieval roofs, Baroque silhouettes. However, these elements have no historical anchoring.

Imitation may be honest (when it does not present itself as restoration), but its semantic depth is always limited: it creates an atmosphere of «once», yet does not reproduce a specific «this was here». The main question is whether stylisation can be considered part of heritage or whether it always remains an architectural decoration.

In Ukraine, the experience of re-creating architectural heritage is extremely diverse. In the period of independence, a number of large-scale projects were implemented: the re-creation of the St Michael's Golden-Domed Monastery in Kyiv, the Assumption Cathedral in Poltava, the Transfiguration Cathedral in Odesa and others. These examples demonstrate a wide range of motivations, from restoring lost sacredness to creating symbols of national identity.

At the same time, the experience of the Soviet period is of particular interest. Today, several decades later, it becomes possible to assess these re-creations without ideological layers – not only as architectural objects but also as carriers of a particular model of authenticity.

One of the most illustrative examples is the re-creation of the Pyatnytska Church in Chernihiv, which makes it possible to trace how, in post-war restoration practice, the image of «authentic Old Rus' architecture» was formed – an image that simultaneously embodied scholarly inquiry and the mythologisation of the past [19].

Before the Second World War, the Pyatnytska Church in Chernihiv had the appearance of a Baroque church of the seventeenth–eighteenth centuries with a nineteenth-century belfry. During the bombings of 1941, the building was almost completely destroyed, with only fragments of the foundations and lower masonry courses of the twelfth–thirteenth centuries surviving, revealed through archaeological investigation. These remnants became the basis for the subsequent re-creation carried out under the direction of Petro Baranovskyi in 1944–1972 (Fig. 5).

Fig. 5. The Pyatnytska Church in Chernihiv. Before destruction and after re-creation

The work was based not on direct visual sources, images or drawings of the original church which did not exist but on archaeological research and comparative analysis of Chernihiv monuments from the pre-Mongol period. The reconstructed volume reproduced a hypothetical image of an Old Rus' church, while all later historical layers were removed. Thus, in the post-war re-creation, the Baroque church was transformed into an idealised image of «authentic Rus'» – a materialisation of an imagined past that had been preserved neither in sources nor in memory.

In this case, the re-creation acquired falsification features, creating the illusion of historical truth without marking its hypothetical character. Today, the Pyatnytska Church functions as an active place of worship, in which the life of the religious community continues. In this way, the new form has ultimately become fixed in public consciousness as «authentic», which further complicates the assessment of its authenticity.

Such cases raise complex questions for researchers: what happens to authenticity when the hypothetical acquires life, and the imagined is accepted as one's own? Can an object that originated as a falsification form of re-creation acquire features of authenticity over time through acceptance, use and incorporation into cultural memory? At what moment does re-creation cease merely to restore the past and begin to produce its own history?

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More than half a century of the Pyatnytska Church's existence shows that, at a certain point, the hypothetical may become living, and this raises the question: is authenticity measured only by origin, or also by the duration of cultural life?

Conclusions. The proposed forms demonstrate that «re-creation» manifests in multiple ways but shares a common foundation: in each case, it functions as a means of engaging with the past within present-day conditions. These forms make it possible to observe how a society conceptualises its past, whether by seeking accuracy or by constructing an interpretative image. In this regard, re-creation operates not as a technical action but as a cultural practice.

Despite their differences, all forms of re-creation exhibit a shared feature: they not only reproduce an image of the past (including an imagined one) but also create conditions for its renewed experience and interpretation. Under certain circumstances, re-creation may generate a new form of authenticity by establishing a framework in which the past interacts with the present. At the same time, this framework contains inherent ambiguities, as factual and imagined elements, memory and reconstructed representations may overlap or shift in meaning. Within this zone of uncertainty, a contemporary understanding of re-creation emerges as a process through which society repeatedly defines what it recognises as «authentic».

A question that remains open for further research is whether a falsified or interpretative form of re-creation can become living heritage when it is accepted, used and incorporated into collective memory.

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ВІДТВОРЕННЯ АРХІТЕКТУРНОЇ СПАДЩИНИ ЯК ДЖЕРЕЛО АВТЕНТИЧНОСТІ

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Анотація. Проблема відтворення архітектурної спадщини традиційно перебуває у полі суперечливих оцінок. Класична доктрина, сформована Венеційською хартією, трактувала автентичність через матеріальну субстанцію пам'ятки, тому будь-яке відтворення розглядалося як фальсифікація. Водночас історичний досвід свідчить: коли втрачено не лише матерію, а й сам простір пам'яті, відтворення стає єдиним засобом повернення культурної тяглості. Наприкінці XX – на початку XXI століття під впливом Нараського документа, Бурра-хартії та Ризької хартії поняття автентичності вийшло за межі матеріальної субстанції, охопивши культурні, соціальні й смислові виміри, а разом із цим змінилося й розуміння самого відтворення.

Метою дослідження є обґрунтування відтворення як культурного акту, здатного породжувати власну автентичність. Методологічна основа дослідження спирається на інструменти архітектурно-реставраційної діяльності та міждисциплінарні підходи. Поєднання історико-аналітичного, порівняльного, системно-структурного й герменевтичного методів дало змогу розглядати відтворення не лише як технічну дію, а як культурний акт, у якому архітектура стає носієм пам'яті й осмислення минулого.

У результаті було запропоновано концептуальну модель множинності автентичності (матеріальний, функціональний, контекстуальний і концептуальний виміри) та розроблено типологію форм відтворення: наукову, репрезентаційну, адаптивну, імітаційну й фальсифікаційну. У статті розглянуто дві полярні форми: наукова та фальсифікаційна, як приклади протилежних стратегій взаємодії між автентичністю й сучасністю.

Показано, що відтворення не є антиподом автентичності: воно може виступати її джерелом, створюючи умови для повторного переживання й осмислення минулого. У цьому процесі справжнє та уявне, пам'ять і реконструйований образ постійно взаємодіють, формуючи нову, динамічну автентичність. Відкритим залишається питання, чи може фальсифікаційне відтворення з часом перетворитися на живу спадщину, прийняту суспільством як власну.

Ключові слова: автентичність, архітектурна спадщина, форми відтворення, ідентичність, фальсифікація.

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URBAN PLANNING PRINCIPLES AND GENERAL APPROACHES TO THE CONCEPT OF RESTORING URBAN AREAS AND CITIES THAT WERE SUBJECT TO DESTRUCTION

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Abstract. The purpose of the work is to develop basic urban planning principles and conceptual foundations for the reconstruction of highly urbanized territories that have been destroyed for the tasks of restoring the urban settlement system. An analysis of the experience of restoring cities and territories in the post-war period was conducted. Positive examples are based on an integrated approach with compliance with two conditions – the involvement of local communities and the development of comprehensive development strategies. situational response – when solving the tasks of urban development, provided many negative consequences of a significant scale. At the initial stage of anti-crisis management, the priority task is to update the city's general plan. The general plan acts as a key document that formalizes the rules, priorities and tasks of urban development activities.

The restoration of territories in conditions of reduced urban potential has a number of specific features: a decrease in population, loss of industrial production, as well as the degradation of transport and engineering infrastructure. This is accompanied by a general deterioration in the qualitative and quantitative indicators of the development of the urban environment.

During the development of the updated general plan, modern principles of spatial development should be laid down: safety, environmental friendliness, autonomy, energy efficiency, convenience and comfort, transport accessibility, creation of conditions for employment.

It is proposed to structure the restoration process by hierarchical levels and types of objects. It is also worth identifying the subjects of management related to reconstruction and forming an information package for planning and implementing design solutions.

The matrix for analyzing planning units of destroyed territories is proposed as a tool that allows for typology, determining priorities and creating a basis for forming regulatory regulation of restoration. It is proposed to use a subject-oriented restoration model.

Keywords: urbanized areas, reconstruction, rebuilding, restoration, master plan, microdistrict, urban planning, building typology.

Introduction. The restoration and reconstruction of the country in the post-war period is an extremely difficult task, given the scale of destruction, damage, and socio-economic and demographic factors. The war has affected different regions of Ukraine in different ways. For some regions, the scale of physical destruction is relatively small. The reconstruction of what has been destroyed is fully in line with current development plans. For the regions of eastern Ukraine, where the front line moved over a long period of time, the destruction was widespread and territorial in nature. The scale and nature of the destruction is comparable to that of a settlement, administrative unit, or territorial entity. The process of rebuilding and restoring objects does not involve individual physical objects such as houses, industrial enterprises, or structures, but rather settlements, engineering and technical systems, and territorial settlement systems. In other words, the scale of the tasks is comparable to the level of adjustment of master plans with corresponding physical and time indicators. A retrospective analysis of the reconstruction of the USSR after World War II provides examples of mistakes made at that time. The administrative-command economy set the restoration of industry as its main goal and task. These tasks were carried out using coercion and administration. Rapid urbanization and the large rural population at that time served as a resource for industry. Another resource was forced labor. As a result, after the collapse of the USSR, a significant part of the industry (focused on the defense sector) proved to be inefficient and burdensome. Industrial regions and single-industry towns fell into a protracted crisis and depression. The very concept of prioritizing the development of means of production imposed on a planned economy proved ineffective. The concept of urban development, established in the late USSR, was progressive in a certain sense at that time, but the implementation of the provisions of the master plans of the cities of the Ukrainian SSR led to large-scale imbalances, restrictions on the development of cities, environmental problems, and structural chaos [1]. Thus, as can be seen in certain urban planning decisions, situational responses to the tasks at hand led to many negative consequences on a large scale [2].

Analysis of the latest research and publications. The issue of post-war reconstruction has been analyzed and researched by a large number of scholars. Differences in approaches and directions are determined by the scale, location, and time periods of armed conflicts. Since World War II, Europe has not faced a war of such intensity, scope, and scale of destruction. A distinctive feature is the conduct of hostilities in highly urbanized areas. In these conditions, the front line means the formation of a zone of complete destruction. The absurdity of the goals and preconditions of war also aggravates its consequences. The experience of the reconstruction of European countries and the USSR [3-5] is of scientific interest in the direction of "working on mistakes".

The reconstruction of the Balkan countries provides experience of positive and negative concepts and approaches to reconstruction. The countries of the Middle East have certain regional characteristics, with both positive and negative examples of reconstruction concepts.

Ukraine has not faced similar problems and is therefore not yet ready to offer a clear, comprehensive reconstruction program. The scientific and methodological foundations for the country's recovery are an important and urgent task at the national level. In recent years, thorough domestic research has been devoted to this issue [6-11].

The purpose of the work. Development of basic urban planning principles and conceptual foundations for the restoration of urbanized areas and cities that have suffered destruction, for the purposes of updating the system of urban settlements and the planning structure of the eastern region of Ukraine.

Materials and methods. System analysis and statistical studies were used.

Main material and results. The fourth year of the war allows us to draw some preliminary conclusions. We can assume that military-civilian administrations – city and regional – are not instruments of development. Military-civilian administrations are created as instruments of crisis management during difficult periods of war or special circumstances. Regional and urban development is a much more complex task, operating in time categories of decades and relying on development programs that define the general principles, foundations, and concepts of recovery. Unlike plans, programs are not focused on specific indicators or target figures. Programs are aimed at implementing goals, achieving specific structural changes, and achieving quality parameters for the urban environment.

Crisis management can provide impetus – if a scientific and methodological approach is established, appropriate conditions are created, tasks and a management structure are formed – in the

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form of an urban development working group. Such a working group, within the administrative-territorial unit – city, urban community – is structured according to the rank of tasks, should be headed by a chief architect, and include an urban planner with relevant professional education.

The task at hand in the first stage of crisis management is to revise and update the city's master plan. The master plan is a document that formalizes the rules and objectives of urban development [12-16]. The master plan is used as a tool for the restoration and balanced development of territories. The master plan must be expedient, effective, balanced, and transparent. Its key role is to systematize up-to-date information on demographic, social, and economic indicators that reflect the real state of the community: its development or decline. It is on the basis of the master plan that programs for prospective development are formed and priority areas for the restoration and expansion of urban territories are determined. Realistic restoration plans should be based on actual data and the current needs of the population. At the same time, the master plan is an important source of information for investors when making decisions about capital investment. Information about the housing market, commercial real estate, and non-residential land plots is particularly sensitive. The master plan also allows for the compensation of shortcomings caused by market distortions. These include distortions in land values and a lack of interest among private investors in financing social or environmental infrastructure, which ultimately reduces the attractiveness of the territories. In addition, the problem of information asymmetry is addressed: internal market participants have more knowledge about local specifics than external investors.

Territorial recovery after hostilities poses particular urban planning challenges: population decline, loss of industrial potential, and degradation of transport infrastructure [17]. Recovery is taking place against the backdrop of a decline in the quantity and quality of the urban planning base, which makes these processes particularly difficult.

Despite this, the reconstruction process must be based on the fundamental principles of sustainable urban development: improving convenience for residents, a safe and comfortable environment, environmental friendliness, autonomy, energy efficiency, transport accessibility, the creation of new jobs, and the provision of a full range of social services in accordance with state standards.

International practice shows that for the effective restoration of degraded areas, it is necessary to focus investment on the development of infrastructure – transport, engineering, and the creation of new jobs. Special attention should be paid to the preservation of the natural environment as a prerequisite for sustainable development.

The master plan also addresses the social development of the urban environment: it provides for the rational planning of the street and road network, the location of kindergartens, schools, parks, green areas, and recreational spaces. In addition, it sets out restrictions and requirements for environmental protection, maintaining a balance between urbanization and natural resources. Since the master plan has the characteristics of a regulatory act, it must undergo an approval and adoption procedure in accordance with the provisions of the legislation on regulatory activity. Approval of the master plan involves publication, public discussion, regulatory impact analysis, and subsequently, procedures for monitoring this impact must be provided for.

The current challenges and organizational constraints in the reconstruction process are due to time constraints and the scale of the destruction. The key problem lies in the urgency of the situation, which requires quick decision-making and tight deadlines for the development of recovery plans and programs. Existing studies emphasize the lack of well-developed general scientific and practical approaches to the organization of recovery processes, which is particularly acute in wartime [18].

Among the main challenges caused by the war, the following can be highlighted: population decline, which has a persistent negative trend; loss of industrial potential due to the destruction or damage of production facilities; partial destruction of infrastructure, with a simultaneous decline in the population of many administrative-territorial communities; the need to formulate approaches to decision-making on the scale and nature of the reconstruction of settlements – partial or complete; the need to identify the responsible authorities and procedures for making management decisions on reconstruction.

The content of reconstruction programs, as well as the initial data for their preparation, should cover a wide range of interrelated issues. Already at the initial stage of organizational planning, a number of burdensome circumstances can be expected:

– shortage of qualified specialists;
– limited time frame for preparing urban planning documentation;
– difficulty in objectively assessing the extent and nature of the damage;
– uncertainty regarding the legal status of ownership, inheritance, and property rights.

In response to these challenges, it is advisable to develop a generalized model for the restoration of settlements affected by large-scale destruction. Such a model should [17, 19]:

– define hierarchical levels and objects of reconstruction (territorial, sectoral, infrastructural);
– outline management entities and types of activities within the scope of reconstruction;
– structure the reconstruction information package – a list of data necessary for decision-making;
– formalize design decisions for the reconstruction of individual objects and functional elements.

Table 1 provides an example of a planning unit analysis matrix (using the city of Rubizhne as an example). The cities of Lysychansk, Severodonetsk and Rubizhne in the agglomeration received updated master plans after 2015. Urban planning documentation was reviewed and adjusted to reflect the situation caused by the occupation of part of the region and the formation of a demarcation line. The master plans for the cities were approved in 2023-24 with the aim of forming a framework document. Changes to urban planning documentation and adjustments to master plans are expected during the reconstruction phase, taking into account the urban planning rationale for the actual state of the settlements. Option/concept of restoration/reconstruction1 is proposed for consideration by individual planning units of the city master plan, taking into account the urban planning analysis of the feasibility of the functional use of land plots. The procedure for developing, updating, amending, and approving urban planning documentation [14, 15] is proposed to be supplemented with an analysis of the concepts of functional use of planning units. A simple "yes-no" dichotomy is supplemented with a SWOT analysis of urban planning rationale.

The city master plan serves as a basic tool for identifying and analyzing planning units that share common typological features, types of damage, functional purpose, and spatial interconnectivity [14]. The identification of such units and their separate processing – with the development of reasonable scenarios and directions for restoration – allows for the rapid accumulation of primary information necessary for strategic decision-making.

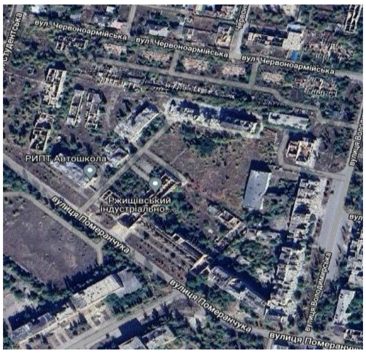
Generalised, deductive reconstruction decisions are recorded in urban planning documentation at the city or territorial community level. The general model for the reconstruction of settlements that have suffered large-scale destruction provides for:

– the definition of hierarchical levels and objects of reconstruction;
– generalization of management entities and types of activities;
– formation of an information package for reconstruction;
– formalization of design decisions for individual objects and elements of reconstruction.

Conclusions:

1. Effective planning is based on fundamental urban planning principles that must be taken into account when renovating urban areas in eastern Ukraine. These include: safety and quality of the environment, environmental friendliness, autonomy and energy efficiency, transport accessibility, creation of new jobs, and infrastructure that meets the real needs of the population. The problems of modern post-war urban reconstruction include the risk of a "budget trap" in single-function settlements. Young people, as an active part of the population, are leaving the area en masse, while socially vulnerable groups are unable to ensure sustainable development, which provokes a recessionary spiral of demographic and economic degradation. In such conditions, it is important to balance the functional content of cities in accordance with their demographic potential, both at the present moment and taking into account long-term forecasts. Alternative scenarios should also be considered, including: complete or partial reconstruction of a settlement; relocation of a new settlement to another area; or demolition of a destroyed settlement with subsequent recultivation.

Table 1 – Example of a planning unit analysis matrix (using Rubizhne as an example)

No	Planning unit	Parameters	Status. Typological description	Option/concept of restoration[1]
1	2	3	4	5
1	 	Rubizhne Industrial Pedagogical College. Founded in 1944. 730 students. 109 employees, including 50 teachers. Relocated to Kolomyia, Ivano-Frankivsk region.	The college is located on a 6-hectare site. The academic building (1939), workshops, dormitory, sports grounds, and driving course training ground. Completely destroyed. The main building is beyond repair.	Change of functional purpose together with the site. *Restoration is possible only in the case of the formation of an educational institution with complete reconstruction of the complex.
2		Rubizhne Polytechnic College named after Poray-Koshytsia. (1927 Rubizhne Chemical and Mechanical Technical School.) 9 specialties, 290 licensed places	The college is located in a park area. Main building, educational buildings, workshops, dormitory, sports grounds. Private buildings around the perimeter. Completely destroyed. The main building cannot be restored.	Change of functional purpose together with the site. *Restoration is possible only in the case of the formation of an educational institution with complete reconstruction of the complex.
3		Pomeranchuk Street. Old town center.	Forms the planning axis of the old city center. An area of complete destruction. Combines residential buildings with administrative facilities.	Preservation of functional purpose. Restoration is advisable on the basis of developing a new planning solution that complies with the updated master plan for the city.
4		Luhansk State Medical University Complex	A separate complex located in the northern part of the city. Relatively preserved.	Preservation of functional purpose. Easy adaptation for educational institutions. Rational structure of the site, convenient transport links.

Continuation of Table 1

1	2	3	4	5
5		The Khimikov-Gorky residential area	Yuzhny residential area, Zabirkyne. Zorya National Nature Park. Forms a separate planning area. Practically destroyed.	Rational structure of the territory, convenient transport links. Preservation of functional purpose. Restoration is possible in the event of the reconstruction of the city-forming enterprise NPP Zorya.
6		The individual sector of the city.	Residential houses are almost completely destroyed	Situation analysis. Status determination. Updating the functional purpose of the site. Concept of the site restoration program.
Option/concept for restoration/reconstruction [1] – alternative concepts based on the updated master plan for the city [14, 15]				

2. Such decisions should be made by local authorities, but the standard algorithm for urban planning in post-war conditions is complicated by many factors. An analysis matrix is proposed as the basis for the model.

3. Inter-level coordination is necessary to justify strategic priorities for reconstruction: coordination of planning documents at the local, regional, and national levels. An important task is to develop adaptive models for the restoration of territories that have suffered various types of destruction, taking into account their functional load, typology of development, level of engineering support, and population density.

4. The formation of analysis matrices for planning units in destroyed territories is the foundation for building an adaptive reconstruction model. It should: structure the restoration at the level of territories, objects, and functions; ensure coordination between management entities; lay the groundwork for regulatory procedures; and ensure the prompt formalization of project decisions in accordance with the current situation on the ground.

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МІСТОБУДІВНІ ПРИНЦИПИ ТА ЗАГАЛЬНІ ПІДХОДИ ДО ЗАСАД ВІДНОВЛЕННЯ УРБАНІЗОВАНИХ ТЕРИТОРІЙ ТА МІСТ, ЩО ЗАЗНАЛИ РУЙНАЦІЇ

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Анотація. Метою роботи є розробка основних принципів містобудування та концептуальних засад реконструкції високоурбанізованих територій, що зазнали руйнувань, для завдань відновлення системи міських поселень. Проведено аналіз досвіду відновлення міст і територій у післявоєнний період. Позитивні приклади базуються на комплексному підході з дотриманням двох умов – залучення місцевих громад та розробка комплексних стратегій розвитку. Ситуативне реагування – при вирішенні завдань містобудівного розвитку, що супроводжувалося багатьма негативними наслідками значного масштабу. На початковому етапі антикризового управління пріоритетним завданням є оновлення генерального плану міста. Генеральний план виступає ключовим документом, що формалізує правила, пріоритети та завдання містобудівної діяльності.

Відновлення територій в умовах зниженого міського потенціалу має ряд специфічних особливостей: зменшення чисельності населення, втрата промислового виробництва, а також деградація транспортної та інженерної інфраструктури. Це супроводжується загальним погіршенням якісних і кількісних показників розвитку міського середовища.

Під час розробки оновленого генерального плану слід закласти сучасні принципи просторового розвитку: безпека, екологічність, автономність, енергоефективність, зручність і комфорт, транспортна доступність, створення умов для зайнятості.

Пропонується структурувати процес відновлення за ієрархічними рівнями та типами об'єктів. Варто також визначити суб'єктів управління, пов'язаних з реконструкцією, та сформувати інформаційний пакет для планування та реалізації проектних рішень.

Матриця для аналізу планових одиниць зруйнованих територій пропонується як інструмент, що дозволяє проводити типологію, визначати пріоритети та створювати основу для формування нормативно-правового регулювання відновлення. Пропонується використовувати предметну модель відновлення

Ключові слова: урбанізовані території, реконструкція, відбудова, відновлення, генеральний план, мікрорайон, містобудування, будівельна типологія.

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NUMERICAL MODELING OF THE IMPACT OF COMPLEX LOADS ON BUILDING MATERIALS

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Abstract. The article is devoted to the urgent problem of predicting the durability of building materials and structures exposed to complex multifactorial loads, including mechanical, thermal, seismic, and corrosive effects. Current trends in construction, especially in areas with high risks of military damage and natural disasters, require scientifically grounded methodologies for assessing the performance of materials under real operating conditions. The study presents a comprehensive analysis of numerical modeling methods, with a particular focus on the finite element method (FEM). This approach enables detailed reproduction of the stress–strain state and makes it possible to account for nonlinear interactions between different types of loads, which is essential for accurate predictions of material service life. Special attention is paid to algorithms that integrate mechanical, seismic, and thermal effects into a unified model, as well as the application of combined methods, including the boundary element method, the Monte Carlo method, and finite differences. The proposed numerical schemes were validated against experimental data, confirming high accuracy with deviations not exceeding a few percent. An additional innovative aspect of the research lies in the integration of classical numerical methods with machine learning technologies, particularly deep neural networks, which allow the consideration of complex nonlinear degradation patterns of materials over time. The study also emphasizes the integration of numerical models with monitoring systems based on IoT sensors. Such an approach ensures real-time dynamic control of the technical state of building structures and enables the timely identification of critical deviations. It has been demonstrated that the application of these algorithms not only improves the accuracy of residual life predictions but also significantly reduces costs by implementing resource-saving restoration technologies. The conclusions outline future research directions, including the extension of numerical modeling methodologies for novel high-performance materials, the advancement of machine learning techniques, and the creation of fully automated systems for monitoring and predicting the technical state of building structures.

Keywords: durability prediction, complex loads, finite element method, machine learning, neural networks, resource-efficient technologies.

Introduction. Building structures are constantly exposed to complex and dynamically changing external loads, including seismic, wind, static, thermal, and corrosion factors. This problem is particularly arise in the context of the restoration of buildings damaged as a result of military operations, when structures undergo additional damage and material degradation, which significantly complicates their assessment and prediction of further operation [1, 9]. Traditional analysis methods, based on separate consideration of individual types of loads, do not allow for effective consideration of their nonlinear interaction, which may lead to an underestimation of the destruction risks.

The solution to this problem is the use of modern complex numerical methods, in particular the finite element method and boundary element method, which allow integrating different types of loads into a single model. This significantly increases the accuracy of predicting the condition of structures, which is especially important for ensuring the safety and durability of buildings in areas with high seismic activity, aggressive environmental conditions, and in situations associated with military destruction [5, 10].

The integration of numerical models with Internet of Things (IoT) technologies and sensor monitoring systems allows real-time information on the condition of structures and immediate response to potential threats, which is key to making timely decisions on repair and strengthening. The application of these technologies also contributes to the development of new, resource-saving structural solutions that optimize material costs and restoration work.

Thus, the development and implementation of modern numerical methods for modeling complex loads is a critically important task for increasing the reliability, safety, and durability of building structures in conditions where the requirements for their strength and stability are constantly increasing.

Analysis of recent research and publications. Modern scientific literature pays significant attention to the use of numerical methods and algorithms for assessing and predicting the durability of building materials and structures under the influence of complex loads, which is due to the increasing requirements for the safety and stability of structures.

One of the leading directions of modern research is numerical modeling of the influence of corrosion on the structural reliability of reinforced concrete elements. In particular, in [9] the authors performed a detailed analysis using the finite element method (FEM) to predict the bearing capacity of reinforced concrete structures reinforced with carbon fiber reinforced polymer (CFRP) meshes with composite cementitious materials. The study took into account the corrosion of reinforcement and its effect on the strength properties of concrete and reinforcement. The authors use the following relationship to estimate the effective cross-section of reinforcement after corrosion:

$$A_{eff} = A_0(1-\rho_c), \tag{1}$$

where Ae_{ff} – effective cross-section after corrosion; A_0 – initial cross-section; ρ_c – degree of corrosion damage.

In another important study [9], the authors used numerical models to analyze the seismic vulnerability of structures after large earthquakes. They assessed the risks to buildings, taking into account structural features, ground motion, and weighting factors of different risk factors. The empirical and coded seismic vulnerability curves developed by the authors demonstrate high accuracy in estimating structural behavior, especially for steel and reinforced concrete structures. The paper proposes an approach to integrating risk factors:

$$V = \sum_{i=1}^{n} w_i F_i, \tag{2}$$

where V – overall vulnerability assessment; w_i – risk factor weights; F_i – the importance of a single risk factor.

Also, in [1], numerical models for assessing the impact of seismic loads using a multifactorial approach that takes into account both code and empirical approaches to create building vulnerability curves were investigated. The authors emphasize that the use of such curves is more effective compared to traditional methods, allowing for a better assessment of the risks of damage and destruction of structures.

Methods for predicting the behavior of structures under complex loads are also considered in [5]. The authors use numerical algorithms for modeling static and dynamic loads, where differential equations of motion in the form are solved:

$$[M]\ddot{u} + [C]\dot{u} + [K]u = F(t), \tag{3}$$

where M, C, K – respectively the mass, damping and stiffness matrix; $u, \dot{u}, \ddot{u}$ – vectors of displacements, velocities and accelerations; $F(t)$ – vector of time-varying loads. The obtained results

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of numerical calculations were confirmed by experimental studies, which confirmed the accuracy of the modeling [5].

Numerical models based on the variation approach of the theory of plasticity were used to analyze the durability of masonry under diagonal stresses. The authors [7] investigate the behavior of brickwork under diagonal tension, providing strength criteria and formulas for assessing the condition of masonry:

$$\sigma_t = \frac{F_{max}}{A\cos\theta}, \tag{4}$$

where σ – diagonal tension; F – load force; A – cross-sectional area, and θ – angle of loading relative to the horizontal. The study demonstrates high accuracy of numerical calculations for predicting the strength and durability of masonry.

The issue of durability of repaired reinforced concrete structures in corrosive environments is highlighted in the study [4]. It considers the assessment of the effectiveness of repair materials, where the prediction of degradation is carried out using models based on machine learning. The authors demonstrate that the combination of numerical modeling with neural network algorithms allows to significantly improving the accuracy of predictions and timely plan repair measures [12].

Thus, the analysis of recent studies shows that the integrated use of numerical methods integrated with modern monitoring and machine learning technologies is a promising direction for accurate prediction of the durability of building materials and structures under complex operational loads. This allows significantly increasing the effectiveness of construction measures aimed at protecting and restoring structures, especially in situations associated with the destructive influence of external factors.

Aim and objectives. The purpose of this study is to develop, adapt and further improve modern numerical methods and algorithms for predicting the durability of building materials under the influence of complex loads, including mechanical, seismic, corrosion and thermal factors. The complex and simultaneous effects of these loads can significantly worsen the strength and operational characteristics of building structures, especially in areas with an increased risk of man-made and natural disasters. In this regard, there is a need to create accurate predictive models and algorithms that can take into account nonlinear interactions of various types of loads and provide reliable forecasts of the durability of materials.

The objectives of the study are:

- analysis and systematization of modern numerical methods for modeling the behavior of building structures;
- improving finite element method (FEM) algorithms and other effective numerical approaches for more accurate prediction of structural durability;
- development of mathematical models that allow integrating heterogeneous factors (mechanical, thermal, seismic, corrosion) into a single comprehensive forecasting model;
- experimental validation of developed numerical models using real data and operating scenarios;
- development of recommendations for the practical implementation of numerical algorithms in automatic monitoring systems for building structures;
- assessing the effectiveness of integrating numerical models with machine learning methods to improve the accuracy of predictions of the durability of building structures.

Achieving these goals will allow us to create scientifically sound methods for predicting the residual resource and optimizing repair measures, which will ensure the durability and safety of building structures in operating conditions with a high risk of damage.

Materials and research methodology. The work uses a comprehensive approach to the study of numerical methods and algorithms for predicting the durability of building materials and structures exposed to complex combined loads. Typical reinforced concrete and brick structures typical of civil and industrial construction were selected as the objects of the study [14]. The study is based on the application of numerical methods, such as the finite element method (FEM), the boundary element method (BEM), as well as machine learning methods for analyzing large amounts of data on material degradation. A comprehensive approach to the use of numerical models, combined with modern machine learning methods, allows significantly increasing the accuracy and reliability of predicting the durability of building structures, which is confirmed by validation on experimental data [15].

Research results. The development of numerical methods for predicting the durability of building materials under complex loadings is a key task of modern engineering practice. Taking into account complex mechanical, seismic, temperature and corrosion effects requires the development of accurate mathematical models that can predict the behavior of materials over a long operational period [8].

Modern approaches are based on the use of numerical models that allow assessing the behavior of materials and structures under various operating conditions, including emergency and post-emergency scenarios.

The main numerical methods used to predict the durability of building structures:

• Finite Element Method (FEM).
• Boundary Element Method (BEM).
• Monte Carlo Method.
• Finite Difference Method.

The use of these methods allows for multifactor analysis of structures and assessment of their residual bearing capacity after exposure to destructive factors.

The durability of a building material is determined by its ability to withstand accumulated damage and its residual load-bearing capacity. This relationship can be represented by the equation [2]:

$$D(t) = D_0 + \int_0^t \left(\sigma(t), T(t), C(t), S(t)\right) dt, \tag{5}$$

D(*t*) – degree of material degradation at a point in time *t*; D_0 – initial level of damage; *σ*(*t*) – mechanical load; *T*(*t*) – temperature effect; *C*(*t*) – corrosion processes; *S*(*t*) – seismic loads.

Thus, the durability of a building material depends on the cumulative effect of loads throughout its entire period of operation.

Basic numerical prediction methods. *The finite element method (FEM)* is the main approach for numerical analysis of the strength and durability of materials. It allows you to break the structure into small elements, for each of which the equation of mechanical equilibrium is solved [12]:

$$\left[K\right]u = F, \tag{6}$$

K – structural stiffness matrix; *u* – node displacement vector; *F* – vector of external loads.

FEM is used to assess the stress-strain state of materials, especially when analyzing reinforced concrete structures damaged by seismic or wind impacts.

The Boundary Element Method (BEM) is an alternative to FEM and is used to analyze complex boundary conditions of structures, such as the interaction of concrete and reinforcement with partial loss of bearing capacity. The basic equation of this method is [9]:

$$\left[B(x)\right]q = D(x), \tag{7}$$

B(x) – deformation transformation matrix; *q* – displacement vector; *D(x)* – vector of internal forces.

The Monte Carlo method is used for stochastic simulations where material parameters may vary due to random factors such as corrosion, temperature cycling, structural inhomogeneities. It is based on numerous iterations to obtain a probability distribution of the material's strength.

The probability of the failure is:

$$P_f = \frac{N_f}{N}, \tag{8}$$

P_f – probability of the failure; N_f – number of cases where limit loads were exceeded; *N* – total number of simulations.

The finite difference method is used to model the diffusion of corrosive particles in concrete structures. It allows predicting the rate of penetration of aggressive substances into concrete:

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2}, \tag{9}$$

C – concentration of corrosive agents; D – diffusion coefficient; x – coordinate in the material; t – time.

The combined use of numerical methods provides accurate prediction of the durability of building structures. The finite element method is the most effective approach for modeling the strength of structures. The Monte Carlo and finite difference methods allow assessing the risks of corrosion and temperature loads [6].

The impact of repairs on the durability of structures. The study [2] emphasizes the importance of correctly selected and implemented repair technologies to ensure the long-term operation of building structures. The main result of this study is a mathematical model that describes the relationship between the quality of repair work and the predicted service life of restored building elements. To assess the impact of repairs on the durability of structures, the authors developed a special probability distribution function:

$$P(t) = 1 - e^{-\lambda t}, \tag{10}$$

$P(t)$ – probability of maintaining the operational characteristics of the material after repair over time t; λ – degradation coefficient, which depends on the quality of the repair, operating conditions and the type of materials used during the restoration of the structure.

According to the results obtained, the degradation coefficient (λ) varies significantly depending on the selected methods and the quality of the repair. The study found that the use of high-strength materials and strict adherence to the repair processes can provide significantly lower values – of the degradation coefficient, and, accordingly, greater durability of structures [3].

The distribution function can be written as follows:

$$P(t) = 1 - e^{-(\lambda_m + \lambda_e + \lambda_q)t}, \tag{11}$$

λ_m – coefficient characterizing the quality of materials used for repairs;

λ_q – coefficient depending on the quality of repair work;

λ_e – coefficient related to operating conditions after repair.

The values of these coefficients, determined experimentally, are given in Table 1.

Table 1 – Degradation coefficients depending on the quality of repair

Repair quality	λ_m, year $^{-1}$	λ_e, operating conditions, 1/ year	λ_q, quality, 1/ year
Low	0.12	0.08	0.09
Medium	0.08	0.06	0.05
High	0.03	0.02	0.01

Table 1 clearly shows that high-quality repair work using appropriate materials and taking into account operating conditions can reduce the total degradation coefficient to a value of λ = 0.06 1/ year, which ensures a projected period of operation of repaired structures of up to 15–20 years, confirming the high effectiveness of such measures.

The graph in Figure 1 shows the dependence of the probability of maintaining the strength of building structures after repair on the time of operation at different levels of repair work quality. It is obvious that the lower the degradation coefficient λ (which is achieved due to better quality of materials, work performance and favorable operating conditions), the slower the serviceability of the structure decreases over time [11].

In particular, with high repair quality (λ = 0.06), even after 20 years, the probability of maintaining the strength of the structure remains about 70%, which indicates the effectiveness of the applied repair technologies. At the same time, with average repair quality (λ = 0.15), the probability of strength after 20 years drops to 5%, and with low quality (λ = 0.36), the strength is almost completely lost in 5-7 years (the probability exceeds 90%).

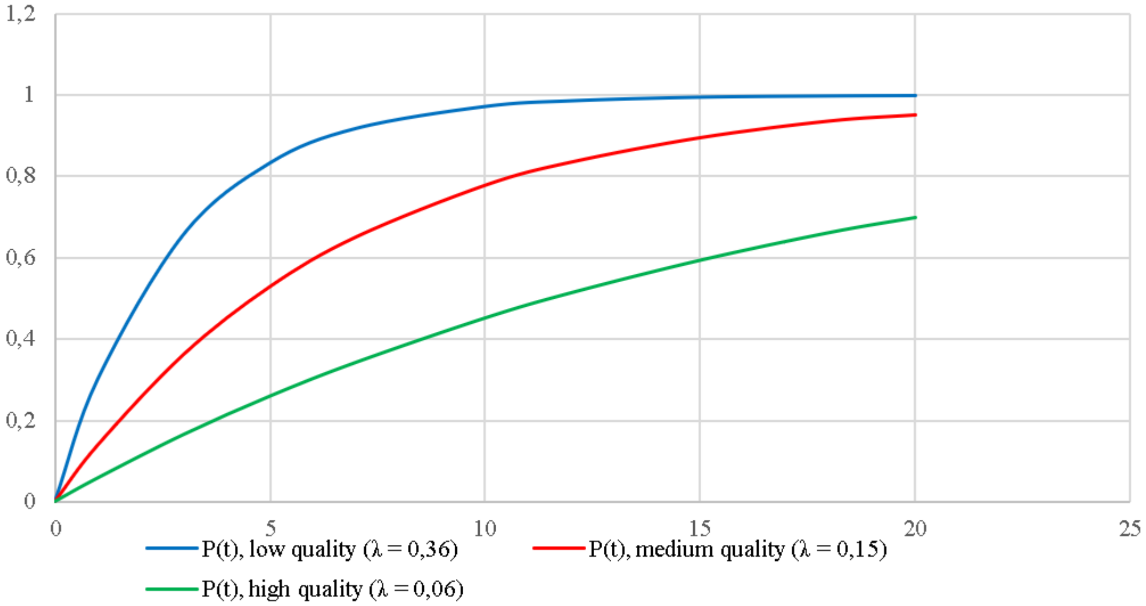

Fig. 1. Curves of the probability of maintaining strength after repair *P* on time *t*

The graph clearly confirms the critical importance of high-quality repairs to ensure long-term operation of structures, allowing to clearly assess the benefits of resource costs for high-quality restoration technologies. The results of the study indicate the importance of quality control of repair work, the correct choice of materials and technologies to achieve high durability of building structures. The use of the presented numerical models and forecasting algorithms allows ensuring the proper level of operational properties and minimize the costs of repeated repairs [13].

Numerical modeling of temperature effects. Building materials are subject to temperature changes, which can cause their thermal deformation and change in mechanical properties. Temperature loads are especially critical for reinforced concrete and steel structures, as they can lead to uneven expansion of materials, the formation of internal stresses and microcracks.

For numerical modeling of temperature effects, the thermal expansion equation is used:

$$\epsilon_{th} = \alpha \Delta T, \tag{12}$$

ϵ_{th} – thermal deformation (elongation of the material); α – coefficient of thermal expansion of the material, 1/°C; ΔT – temperature change (°C).

This dependence allows us to estimate how much the linear dimensions of building materials change with temperature changes.

Prolonged exposure to high temperatures causes changes in the mechanical properties of building materials. For concrete and steel, these changes are largely determined by the temperature range and heating rate.

Research [5] shows that with increasing temperature, there is a decrease in the strength of concrete due to dehydration of cement stone. For numerical modeling of this effect, the equation of the dependence of strength on temperature is used:

$$\sigma_T = \sigma_0 e^{-kT}, \tag{13}$$

σ_T – material strength at temperature T; σ_0 – initial strength at 20°C; k – exponential coefficient of strength degradation; T – temperature (°C).

Reinforced concrete has two main temperature factors:

- Expansion of the concrete matrix – concrete expands when heated, which can cause additional internal stresses.
- Reinforcement expansion – Steel reinforcement has a higher coefficient of thermal expansion than concrete, which results in tensile stresses in the concrete.

Thermomechanical stress in reinforced concrete is determined by the equation:

$$\sigma_{th} = E \cdot \epsilon_{th}, \tag{14}$$

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σ_{th} – thermal stress; E – modulus of elasticity of the material; ϵ_{th} – thermal expansion.

Thermal expansion of concrete is an important physical and mechanical parameter that affects the durability and integrity of building structures. Studies show that with an increase in temperature from 20°C to 80°C, the relative expansion of the material increases within 0.02%-0.08%. This dependence is linear, which indicates a proportionality between the change in temperature and the magnitude of deformation. When the temperature increases, the expansion of cement stone and fillers occurs, which causes an increase in the volume of concrete. However, due to different coefficients of thermal expansion of its components, internal stresses may arise that can negatively affect the strength of the material. In massive structures, especially with sudden temperature changes, such deformations can cause the appearance of microcracks and accelerate the process of material degradation.

The study [6] proposes to use the finite element method (FEM) for numerical analysis of thermal effects on materials. The basic equation of thermal conductivity in building materials is:

$$\rho c_p \frac{\partial T}{\partial t} = k\nabla^2 T, \tag{15}$$

ρ – material density; c_p – heat capacity; k – thermal conductivity coefficient; T – temperature at a given point in the material. Solving this equation allows us to estimate how the temperature in a building structure changes over time.

It is recommended to use heat-resistant materials, in particular concretes based on aluminate cements and refractory steels, for critical structures. To reduce the effects of thermal expansion, expansion joints should be designed in large concrete structures. In addition, the calculation of thermal stresses using numerical simulation (FEM) is necessary to assess the durability of materials. Thus, numerical simulation of thermal effects allows for an accurate assessment of the behavior of building materials and predict their durability in changing climatic conditions.

Using machine learning to predict material degradation. The application of machine learning (ML) methods allows to increase the accuracy of predicting the degradation of building materials and optimize their durability. These methods are successfully integrated with numerical approaches, in particular the finite element method (FEM), providing a comprehensive assessment of the state of structures under the influence of various loads (seismic, thermal, corrosion) [12].

The mathematical foundations of degradation prediction using ML to predict the level of degradation of building materials using machine learning methods by building a regression model:

$$D_{pred} = w_1 F_s + w_2 F_c + w_3 F_t + w_4 T, \tag{16}$$

D_{pred} – predicted material degradation (in % or conventional units);

F_s – intensity of seismic loads (e.g. peak ground acceleration);

F_c – degree of corrosion (expressed as a percentage of the loss of reinforcement cross-section);

F_t – the effect of thermal loads (temperature cycles);

T – operating time of the structure (years);

w_1, w_2, w_3, w_4 – weighting factors, which are determined by training the model on experimental data.

According to the results of [5], weighting factors are determined by multifactorial regression analysis of historical data, which ensures the adaptability of the model to different types of structures and operating conditions.

Neural networks allow predicting the behavior of materials and structures, revealing complex, nonlinear relationships. Deep neural networks (DNNs) are effectively used to predict the degradation of building materials:

$$y = f\left(\sum_{i=1}^{n} w_i x_i + b\right), \tag{17}$$

y – predicted level of degradation;

x_i – input factors (temperature, corrosion, seismic loads);

w_i – weight coefficients determined during the training process of a neural network;

b – bias coefficient (bias).

The model is trained on experimental data obtained using sensors located on real objects, which ensures high accuracy of predictions [17].

Statistical metrics such as the coefficient of determination (R_2) and mean square error (MSE) are used to assess the accuracy of machine learning predictions:

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2}, MSE = \frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2, \quad (18)$$

y_i – real degradation values obtained experimentally;

$\hat{y}_i$ – predicted values;

$\bar{y}$ – average value of real degradation;

n – number of observations.

These indicators allow us to quantify the deviation of the model from real data and adjust the learning algorithms [16].

As shown in Figure 2, the use of neural network models provides the highest prediction accuracy among the considered methods, especially in the case of a large number of interacting load factors.

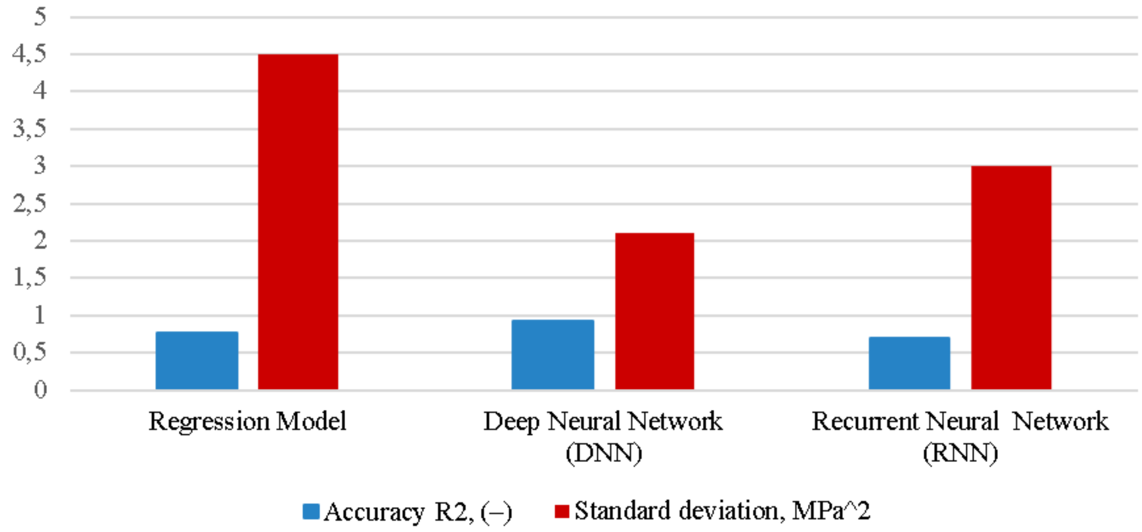

Fig. 2. Comparison of the effectiveness of machine learning algorithms

The integration of numerical methods and machine learning models with IoT allows for real-time monitoring of the condition of building structures. IoT sensors collect data in real time, which increases the efficiency and accuracy of predicting material degradation. This allows for rapid response to threats, timely repairs or reinforcement of damaged structures.

Research in the field of resource-saving technologies allows to reduce costs when restoring structures damaged by military actions. The following approaches are used:

- Using recycled materials for repairs, which reduces costs without reducing reliability.
- Reinforcement with composite materials, which have better strength characteristics at lower weight.
- Rapidly assembled modular structures for the installation of civil defense protective structures, which allows you to quickly ensure safe operating conditions for damaged facilities.

The graph in Figure 3 presents a comparison of machine learning methods for predicting the degradation of building materials according to two main accuracy criteria: root mean square error (MSE) and coefficient of determination (R^2).

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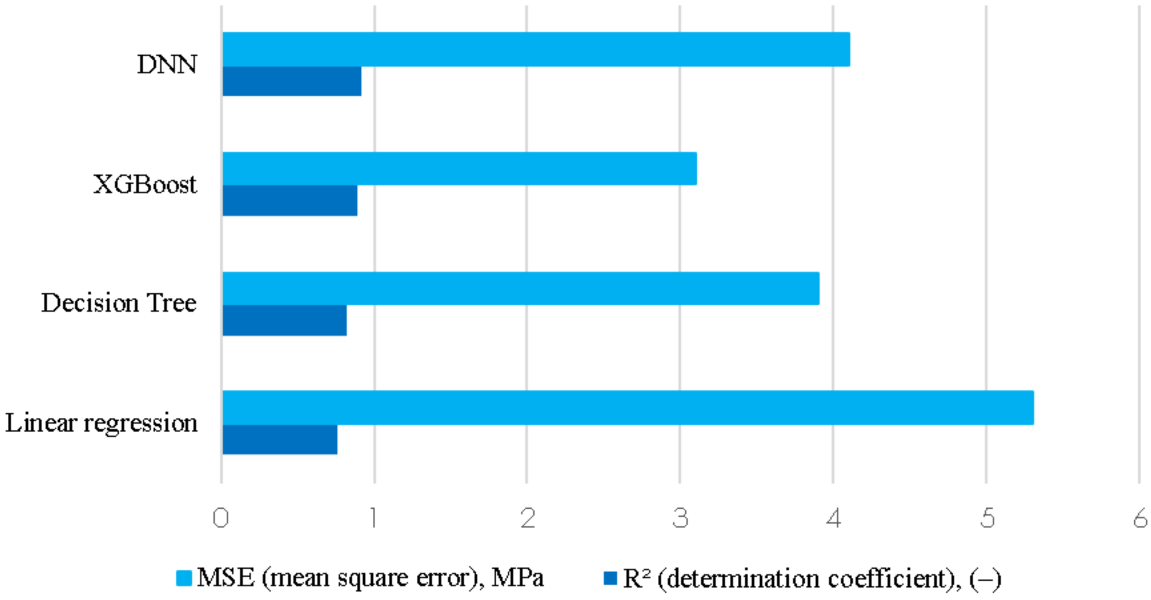

Fig. 3. Comparison of the accuracy of predicting the degradation of building materials by different ML methods

The lowest MSE value (2.1) and the highest coefficient of determination value (R^2 = 0.92) are demonstrated by the deep neural networks (DNN) method, which indicates its high accuracy and reliability in predicting nonlinear patterns of material degradation. Linear regression has the largest error (MSE = 5.3) and the lowest prediction accuracy (R^2 = 0.76), which emphasizes the limited suitability of this method for complex prediction problems. Gradient boosting (XGBoost) and decision trees demonstrate intermediate indicators, which makes them acceptable for problems with less complex nonlinear dependencies. Therefore, it is advisable to use deep neural networks for predicting the durability of building structures, which provide the highest accuracy among the considered methods.

The proposed numerical methods, combined with machine learning algorithms and integrated with IoT, allow for accurate prediction of the degradation of building materials, providing prompt diagnostics and saving resources during the repair and restoration of structures, especially in conditions of increased risk. Further research in this direction will allow for even more effective solutions to the problems of predicting and preventing the destruction of structures, especially in areas of active fighting [12].

Validation of numerical models. Validation of numerical models is a critical step in the process of their development and implementation. To confirm the accuracy of the models, it is necessary to conduct experimental comparisons of the predicted and actual characteristics of building materials under the influence of various types of loads.

Validation of numerical models is carried out using the following approaches:

- Comparison with experimental data – verification of predicted values using laboratory tests on material samples.
- Deviation analysis – determination of the average and maximum difference between numerical and real data.
- Correlation analysis – determination of the degree of relationship between numerical and experimental values.
- Compliance criteria (coefficient of determination R_2, root mean square error RMSE, mean absolute error MAPE) – statistical assessment of the accuracy of predictions.

The experimental tests conducted allowed us to determine the accuracy of numerical models in predicting the behavior of materials under complex loads. The results of the comparison of numerical and experimental data are shown in Figure 4.

The maximum deviation of numerical predictions does not exceed 2.8%, which indicates high accuracy of modeling. The high correlation between numerical and real data confirms the effectiveness of the proposed approaches.

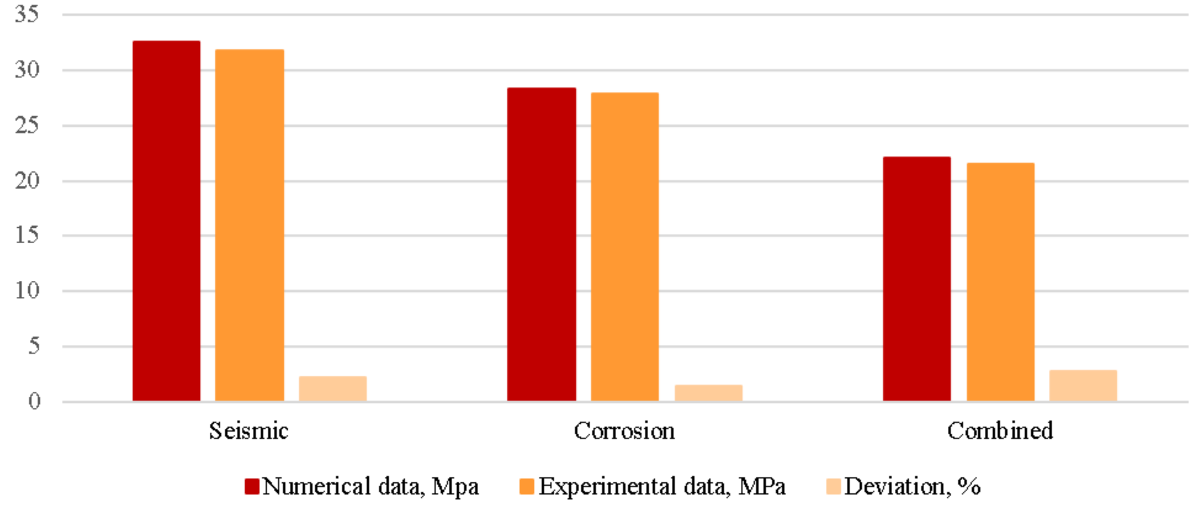

Fig. 4. Validation of numerical models

The following statistical indicators were used to assess the accuracy of numerical models:
The root mean square error (RMSE) is determined by the formula:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}, \tag{19}$$

y_i – experimental values;
$\hat{y}_i$ – values predicted by the numerical model;
n – number of measurements.
The coefficient of determination (R^2) is:

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2}, \tag{20}$$

$\bar{y}$ – the average value of the experimental data.
The mean absolute percentage error (MAPE) is calculated:

$$MAPE = \frac{100\%}{n}\sum_{i=1}^{n}\left|\frac{y_i - \hat{y}_i}{y_i}\right|, \tag{21}$$

These criteria allow for a comprehensive assessment of the accuracy of numerical models under different conditions.

Figure 5 presents a comparative assessment of the accuracy of numerical models: the finite element method (FEM), the boundary element method (BEM), and the finite difference method (FDM). The assessment was carried out using three criteria: root mean square error (RMSE), coefficient of determination (R^2), and mean absolute error (MAPE, %).

As the graph shows, the finite element method (FEM) provides the lowest RMSE (0.52 MPa) and MAPE (1.8%), as well as the highest coefficient of determination R^2 (0.97). This indicates its high accuracy in predicting the behavior of building materials and structures compared to other methods. The largest errors are observed in the finite difference method (FDM), which may indicate the limitations of its application for modeling complex loads and operating conditions of structures. Thus, based on the results obtained, it can be concluded that the finite element method is superior in predicting the durability of building materials and is recommended for widespread use in practical calculations.

Based on the analysis of the accuracy of numerical models, the following practical recommendations can be formulated:

- Numerical models demonstrate high accuracy, providing a maximum deviation of no more than 2.8% from experimental data.

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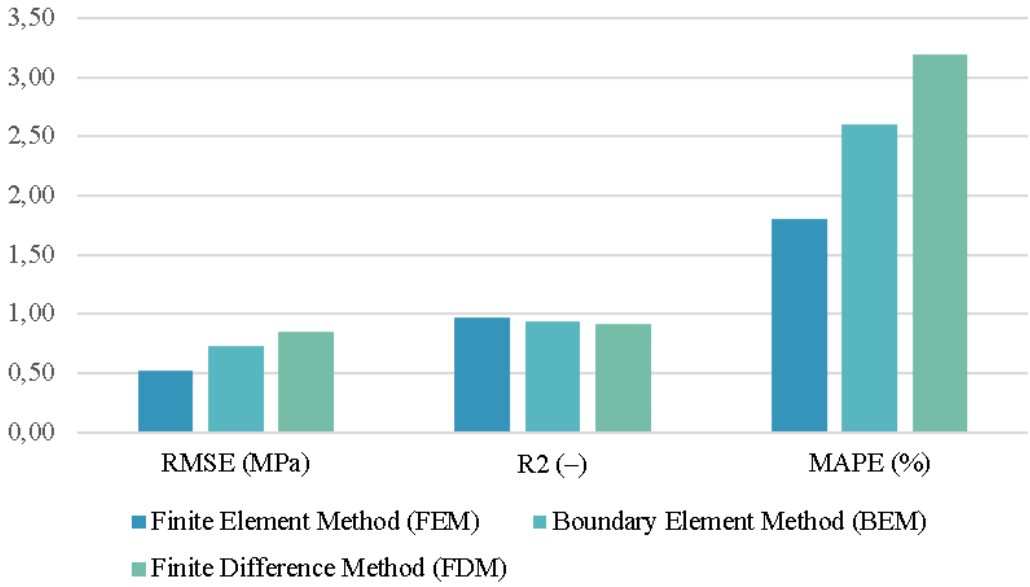

Fig. 5. Assessment of the accuracy of numerical models

- The finite element method (FEM) is the most effective method for predicting the durability of building structures due to its high accuracy and versatility.
- The results of experimental validation confirm the applicability of numerical methods for assessing the condition and predicting the durability of materials and structures.
- Further research should focus on adapting numerical models to more complex operating conditions, such as long-term corrosion effects, repeated loading cycles, and other complex factors.

Thus, the use of numerical modeling allows us to accurately predict the residual life of building structures and make informed decisions regarding their repair, reinforcement, and operation.

Conclusions. The conducted studies confirm that numerical modeling methods are effective tools for assessing and predicting the durability of building materials and structures under complex loading conditions, including seismic, thermal, mechanical and corrosion effects. The most accurate of the numerical methods is the finite element method (FEM), which provides a high level of prediction accuracy (R^2=0.97) with minimal errors (RMSE=0.52 MPa, MAPE=1.8%).

The use of machine learning (ML) methods further increases the efficiency of assessing the degradation of building materials. Deep neural networks (DNN, R^2=0.92, MSE=1.25) and gradient boosting (XGBoost, R^2=0.89, MSE=2.15) demonstrate the best results due to their ability to take into account complex nonlinear dependencies. At the same time, linear regression has a significantly lower accuracy due to its inability to describe the nonlinear behavior of materials. Integration of ML technologies with IoT systems allows you to create dynamic monitoring systems that quickly update numerical models in real time, ensuring timely response to potential threats.

Resource-saving technologies play an important role in the processes of restoring structures after war damage. Their use, in particular the use of secondary raw materials, composite materials, and modular protective structures, allows for a significant reduction in the time and material resources spent on restoring damaged buildings.

The experimental validation of numerical models showed a high correspondence of the predicted data to the experimental results, with the maximum deviations not exceeding 2.8%, which confirms the practical value of the obtained results. Further scientific research should be focused on the creation of hybrid models that combine the advantages of numerical methods and ML algorithms, the study of the behavior of new materials (composites, nanomaterials), as well as the improvement of automated systems for monitoring and forecasting the technical condition of building structures in real time.

Thus, the presented results are of great importance for improving the safety, reliability, and efficiency of building structures, especially in conditions where there are significant risks of complex loads and the possibility of military damage.

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ЧИСЕЛЬНЕ МОДЕЛЮВАННЯ ВПЛИВУ КОМПЛЕКСНИХ НАВАНТАЖЕНЬ НА БУДІВЕЛЬНІ МАТЕРІАЛИ

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Анотація. Стаття присвячена актуальному питанню прогнозування довговічності будівельних матеріалів і конструкцій, що зазнають впливу комплексних багатофакторних навантажень, серед яких механічні, термічні, сейсмічні та корозійні. Сучасні тенденції розвитку будівництва, особливо у зонах підвищеного ризику воєнних руйнувань і природних катастроф, потребують створення науково обґрунтованих методик оцінки стану матеріалів у реальних умовах експлуатації. У роботі проведено ґрунтовний аналіз чисельних методів моделювання, серед яких центральне місце займає метод кінцевих елементів (МКЕ). Саме він забезпечує деталізоване відтворення напружено-деформованого стану та дозволяє враховувати нелінійні взаємодії між різними видами навантажень, що є визначальним для коректного прогнозування довговічності. Особливу увагу приділено алгоритмам інтеграції механічних, сейсмічних і термічних впливів у єдину модель та використанню комбінованих підходів, зокрема методу граничних елементів, методу Монте-Карло й скінченних різниць. Запропоновані авторами чисельні схеми були валідувані на експериментальних даних, що підтвердило високу точність розрахунків, відхилення яких не перевищує кількох відсотків. Додатковим інноваційним аспектом дослідження стало поєднання класичних чисельних методів із технологіями машинного навчання, включно з глибокими нейронними мережами, які дозволяють враховувати складні нелінійні закономірності деградації матеріалів у часі. Значне місце у роботі займає аналіз можливостей інтеграції чисельних моделей із системами моніторингу на основі сенсорів IoT. Такий підхід забезпечує динамічний контроль технічного стану будівельних конструкцій у реальному часі та створює умови для своєчасного виявлення критичних відхилень. Показано, що використання подібних алгоритмів дає змогу не лише підвищити точність прогнозування залишкового ресурсу, а й істотно скоротити витрати завдяки впровадженню ресурсоощадних технологій відновлення. У висновках визначено напрями подальших досліджень: розширення методик чисельного моделювання для нових високоефективних матеріалів, удосконалення методів машинного навчання, а також створення повністю автоматизованих систем моніторингу та прогнозування технічного стану будівельних конструкцій.

Ключові слова: прогнозування довговічності, комплексні навантаження, метод кінцевих елементів, машинне навчання, нейронні мережі, ресурсоощадні технології.

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ПРАКТИЧНА МЕТОДИКА РОЗРАХУНКУ МОНОЛІТНИХ ПЛИТ ПЕРЕКРИТТІВ, ПІДСИЛЕНИХ СТАЛЕВИМИ БАЛКАМИ

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Анотація. Розглянуто метод підсилення монолітних залізобетонних плит перекриттів сталевими балками в нижній зоні. З кінця 1990-х років і по теперішній час житлове і цивільне будівництво в нашій країні базується на монолітно-каркасній технології де переважно застосовуються плоскі плити перекриття. Перекриття найчастіше потребують підсилення в наслідок пошкоджень, викликаних різними причинами або при зміні архітектурно-планувальних рішень. Підсилення таких перекриттів сталевими балками у будівельній практиці застосовується досить часто, особливо у випадках, коли не можливо виконати повне розвантаження конструкції перекриття. Конструктивні рішення такого методу підсилення напрацьовані давно і мають досить багато варіацій. Однак, якщо проаналізувати нормативну базу в сфері реконструкції і підсилення, то можна виявити певну недостачу розрахункових методів для аналізу підсилених конструкцій. Перекриття в системі монолітного каркасу є багатократно статично-невизначеною конструкцією, тому його адекватний розрахунок без застосування сучасних програмних комплексів навряд чи можливий.

Виконано огляд чинної нормативної бази в сфері реконструкції і підсилення. Розглянуто ряд публікацій в фахових виданнях, присвячених цій темі і розрахунковим підходам при проєктуванні підсилень. Проаналізовано конструктивні особливості підсилення розвантажувальними балками. Запропоновано практичну методику розрахунку монолітних плит перекриттів, підсилених балками в нижній зоні за допомогою програмного комплексу ЛІРА-САПР. Методика базується на врахуванні початкового деформованого стану плити перекриття. Розрахунок ведеться кроково-ітераційним методом з врахуванням фізично-нелінійних властивостей залізобетону і життєвого циклу конструкції. Особливу увагу приділено методиці моделювання зони контакту «плита-балка підсилення». Зона контакту моделюється за допомогою односторонніх в’язей, які сприймають тільки зусилля стиску.

Наведений алгоритм розрахунку апробований автором при проєктуванні багатьох об’єктів, які були реалізовані і успішно експлуатуються вже тривалий час.

Ключові слова. Плита перекриття, балка підсилення, модель, розрахунок.

Вступ. В Україні експлуатується значна кількість будинків з монолітними з.б. плитами перекриттів. Необхідність підсилення таких конструкцій в практиці проєктування і будівництва виникає дуже часто. Перекриття найчастіше потребують підсилення в наслідок пошкоджень, викликаних різними причинами або при зміні архітектурно-планувальних рішень (збільшення навантажень, необхідність виконання отворів під нові комунікації і т.п.). Повномасштабна війна ще більше загострила це питання. Виходячи з цього, очевидно, що розробка практичних методів розрахунку підсилених конструкцій з застосуванням доступних програмних комплексів є актуальним питання.

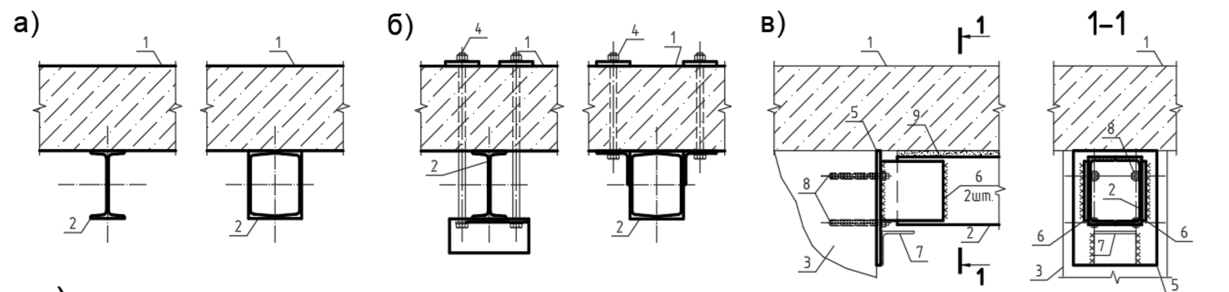
Аналіз останніх досліджень та публікацій. Наукова спільнота будівельної галузі України завжди приділяла значну увагу питанню підсилення і відновлення конструкцій. В роботах [1, 2] виконано ретельне узагальнення минулого досвіду конструювання і розрахунків підсилення залізобетонних конструкцій. Регулярно видаються навчальні посібники [3-5]. У фахових виданнях публікуються та узагальнюються результати експериментальних досліджень різних типів підсилення [6-8]. Науковці розробляють оригінальні методики розрахунку підсилених конструкцій в тому числі і з застосуванням різних програмних комплексів [9-13]. Впроваджуються ефективні рішення для ремонту і повної заміни конструкцій, пошкоджених в наслідок агресії російської федерації [14].

Нормативна база України в частині реконструкції, ремонту і підсилення конструкцій представлена ДСТУ [15], частково ДБН [16, с.35-37], котрі встановлюють загальні вимоги до проєктування і виконання підсилення конструкцій і основ. Технічний стан конструкцій визначається згідно ДСТУ [17]. Розрахунки конструкцій за граничними станами мають виконуватися за загальними правилами згідно ДБН [18, 19]. Навантаження та впливи визначаються за вказівками ДБН [20, 21]. Допустимі прогини і переміщення регламентовано ДСТУ [22]. З іноземних нормативних джерел варто відзначити стандарт США ACI 562 [23], який був розроблений для інтеграції з загальними будівельними нормами. В Європі за відсутності спеціалізованого стандарту застосовуються EN 1990 [24]. Практично всі згадані нормативи в сфері підсилення містять одну спільну рису – методологія розрахунків в них регламентується в досить стислому обсязі, акцент зроблено на загальні вимоги. Такий підхід надає фахівцям-проєктувальникам можливість проявити креативність та гнучкість у процесі оцінки та проєктування підсилення, забезпечуючи при цьому необхідний рівень надійності конструкцій.

Мета та завдання. Розробка практичної методики розрахунку монолітних з.б. плит перекриттів, підсилених сталевими балками в нижній зоні з застосуванням ПК ЛІРА-САПР.

Матеріали та методи дослідження. Аналіз нормативної бази та спеціалізованої літератури в сфері підсилення залізобетонних конструкцій. Побудова розрахункових скінчено-елементних моделей конструкцій, аналіз результатів розрахунків.

Результати дослідження. Підсилення з.б. перекриттів підведенням знизу розвантажувальних металевих балок є, напевно, найпоширенішим і найпростішим технічним рішенням. Найчастіше використовуються прокатні двотаври та коробчасті перерізи зі швелерів (рис. 1). Конструкція балки може виконуватись як з додатковими тяжами так і без них. Рішення без тяжів є кращим з точки зору менших габаритів перерізу і відсутності додаткових пошкоджень плити отворами під тяжі. Балки можуть опиратися безпосередньо на вертикальні елементи каркасу або на інші металеві балки (створюється балкова клітина). Опорні вузли балок найчастіше виконуються шарнірними, за допомогою механічних або хімічних анкерів (рис. 1, в). Створення жорстких опорних вузлів балок підсилення, як правило ускладнене і на практиці реалізується не часто.



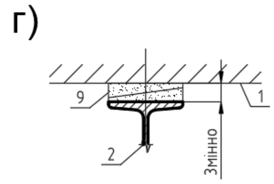


Рис. 1. Деталі підсилення плити сталевими балками:
а – схема влаштування підсилення без додаткових тяжів; б – те ж, з додатковими тяжами; в – приклад опорного вузла балки; г – деталь заповнення зазору між балкою і плитою; 1 – плита, що підсилюється; 2 – балка підсилення; 3 – вертикальні елементи каркасу; 4 – додаткові тяжі; 5, 6 – опорні пластини; 7 – монтажний столик; 8 – анкери; 9 – заповнення зазору (ц.п. розчин та сталеві клини)

На першому етапі, балка підсилення має бути щільно притиснута до низу плити за допомогою домкратів (рис. 2, а). При цьому, щільний контакт між плитою і балкою існуватиме тільки в деякій зоні в середині прольоту (рис. 2, б). Поза цією зоною завжди виникатиме зазор, який заповнюється ц.п. розчином. За необхідності в зазорі можуть бути розміщені елементи розклинювання верхнього поясу балки.

При розробці схеми розташування балок підсилення слід узгоджувати її з архітектурно-планувальними рішеннями (розташовувати балки над перегородками). Це дозволяє покращити естетичний вигляд об’єкта і підвищує вогнестійкість балки. В будь-якому випадку, відкриті поверхі сталевих балок мають бути захищені вогнезахисним покриттям.

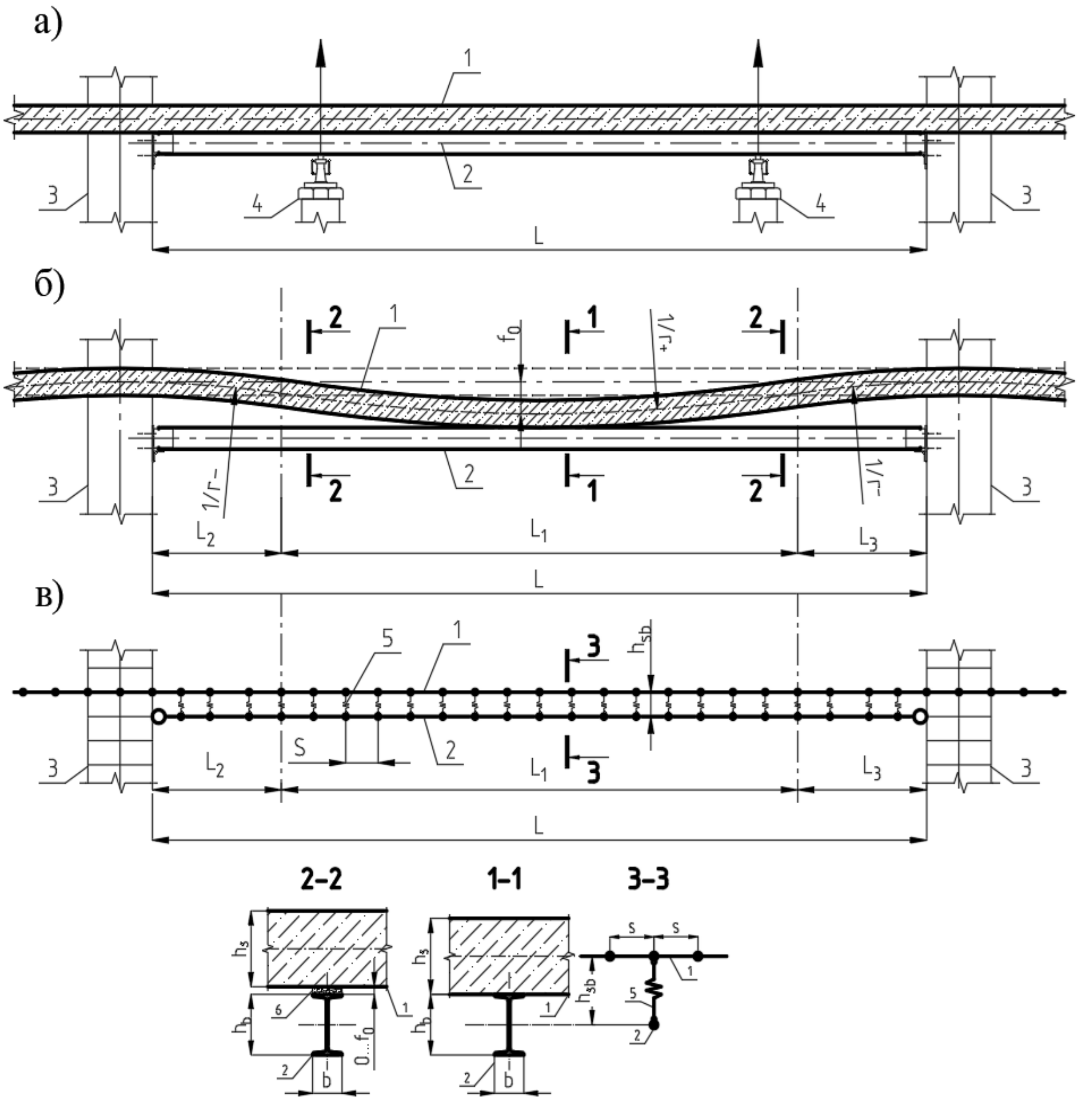


Рис. 2. До складання розрахункової схеми: а – схема влаштування підсилення плити балкою; б – те ж, з гіпертрофованими для наочності деформаціями плити; в – скінчено–елементна інтерпретація схеми; 1 – плита, що підсилюється; 2 – балка підсилення; 3 – вертикальні елементи каркасу; 4 – монтажні домкрати; 5 – односторонні в'язі стиску; 6 – заповнення зазору; L – розрахунковий проліт; L_1 – довжина зони додатньої кривизни; L_2, L_3 – довжини зон від'ємної кривизни; f_0 – початковий прогин плити на момент підсилення; h_s – товщина плити; h_b – ширина балки; h_{sb} – розрахункова висота посиленої конструкції в скінчено–елементній моделі; s – крок тріангуляції моделі

Методика розрахунку, яка пропонується в даній роботі, розроблена для балок без додаткових тяжів (рис. 1, а) і базується на таких основних засадах. На момент підсилення плита перекриття вже отримала певні прогини f_0 (рис. 2, б). На практиці, як правило (але не завжди), може бути знята частина впливу на плиту від ваги перегородок, підлог і, зрозуміло,

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тимчасових навантажень. Прогин від власної ваги плити при більш-менш значних прольотах компенсувати досить складно. В такому випадку, деформована поверхня плити характеризується наявністю зон L_1 додатної кривизни в прольотах і зон L_2, L_3 від'ємної кривизни поблизу опор. В зоні L_1 спільна робота плити і балки підсилення забезпечується силами тертя і має односторонній характер (стиск). В зонах L_2, L_3 спільна робота без додаткових конструктивних заходів неможлива. Підсилення включається в роботу відразу після закріплення балки на опорах і демонтажу монтажних домкратів.

ПК ЛІРА-САПР надає можливість моделювати спільну роботу плити і балки через односторонні в'язі. В бібліотеці скінчених елементів комплексу присутні відповідні елементи, коректність застосування яких теоретично обґрунтована [25]. При кроково-ітераційному розрахунку в'язі, в яких виникає розтяг, автоматично виключаються з розрахунку.

Основні етапи розрахунку продемонструємо на реальному прикладі з власної інженерної практики.

1. Вихідні дані. Прийнято рішення перепрофілювати ділянку 3–поверхової стилобатної частини під ТРЦ. Конструкції каркасу вже побудовані. Переважний крок колон 8.4×8.4 м, перерізи колон 500×500 і 600×600 мм, товщина плити перекриття 300 мм, плита безбалкова і безкапітельна. Поставлена задача: виконати нові прорізи в перекритті по нових об'ємно-планувальних рішеннях (рис. 3). Прорізи мають виконуватися дисковою пилкою, безударним методом. Робоча документація на виконані конструкції в наявності, армування відоме, клас бетону конструкцій відповідає проєкту (С25/30).

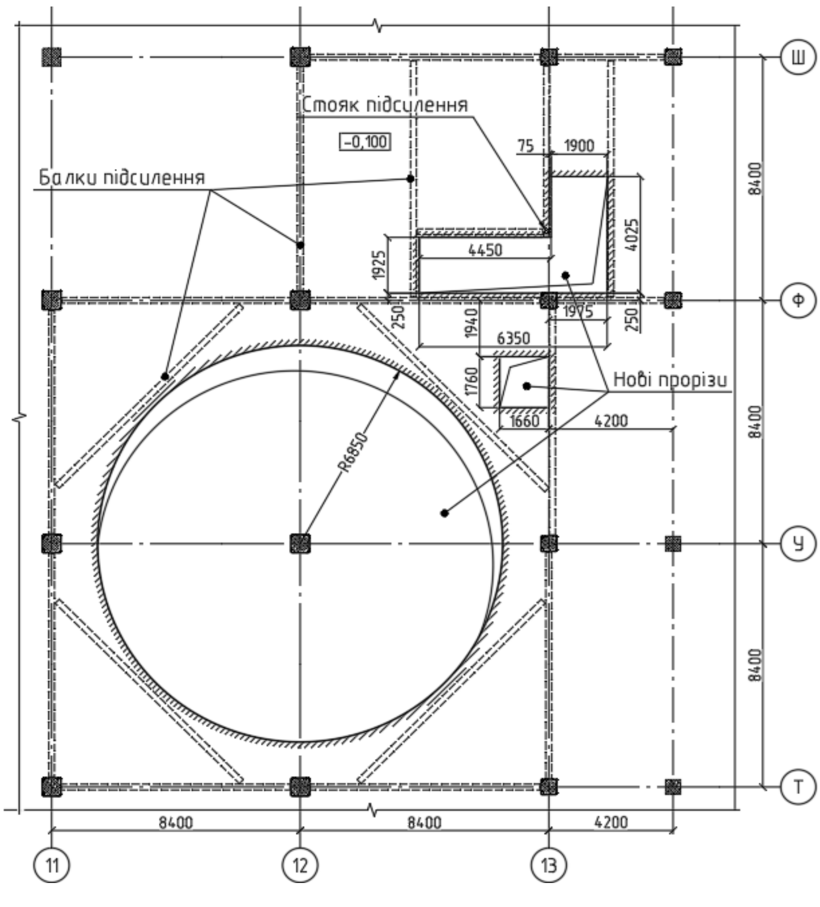

Рис. 3. Фрагмент конструктивного плану з новими прорізами у перекритті і балками підсилення

2. Формування розрахункової моделі. Розрахунок виконуємо в ПК ЛІРА-САПР в фізично-нелінійній постановці. Загальний вигляд розрахункової моделі наведено на рис. 4. Переважний крок тріангуляції плити S=200 мм. Колони каркасу змодельовані скінченим елементом (далі СЕ) типу 210 – фізично-нелінійний стержень; плита перекриття моделюється СЕ типу 242 і 244 – трикутні та чотирикутні фізично-нелінійні елементи оболонки. Зона контакту між плитою перекриття і сталевою балкою моделюється СЕ типу 262 – пружна одностороння в'язь. Щодо моделювання сталевих балок то в ПК ЛІРА-САПР для стандартних прокатних профілів не передбачена можливість врахування фізичної нелінійності, тому балки підсилення моделюються лінійним СЕ типу 10. На перший погляд використання лінійних елементів в кроково-ітераційному розрахунку видається не коректним. Однак, якщо виконати тестові розрахунки з фізично-нелінійними СЕ типу 210 і перерізом, що відповідає стандартному прокатному профілю, то можна впевнитися, що результати як за переміщеннями так і за зусиллями для СЕ 10 і 210 будуть близькими. Тому застосування СЕ типу 10 для практичних розрахунків є виправданим. Для цього типу СЕ в ПК ЛІРА-САПР розроблені підсистеми підбору і перевірки сталевих перерізів, які дуже суттєво економлять час проєктувальника.

3. Моделювання життєвого циклу конструкції виконано за допомогою системи «Монтаж». Виділено 4 монтажні стадії (рис. 4, 5): Стадія 1 – модель містить побудовані конструкції з.б каркасу, завантажені власною вагою; Стадії 2...4 – до моделі додано конструкції підсилення і видалено СЕ нових прорізів, прикладаються постійні навантаження від перегородок, підлог та тимчасові корисні навантаження. Всі навантаження задано згідно з проєктною документацією, з урахуванням вимог чинних норм [20, 21].

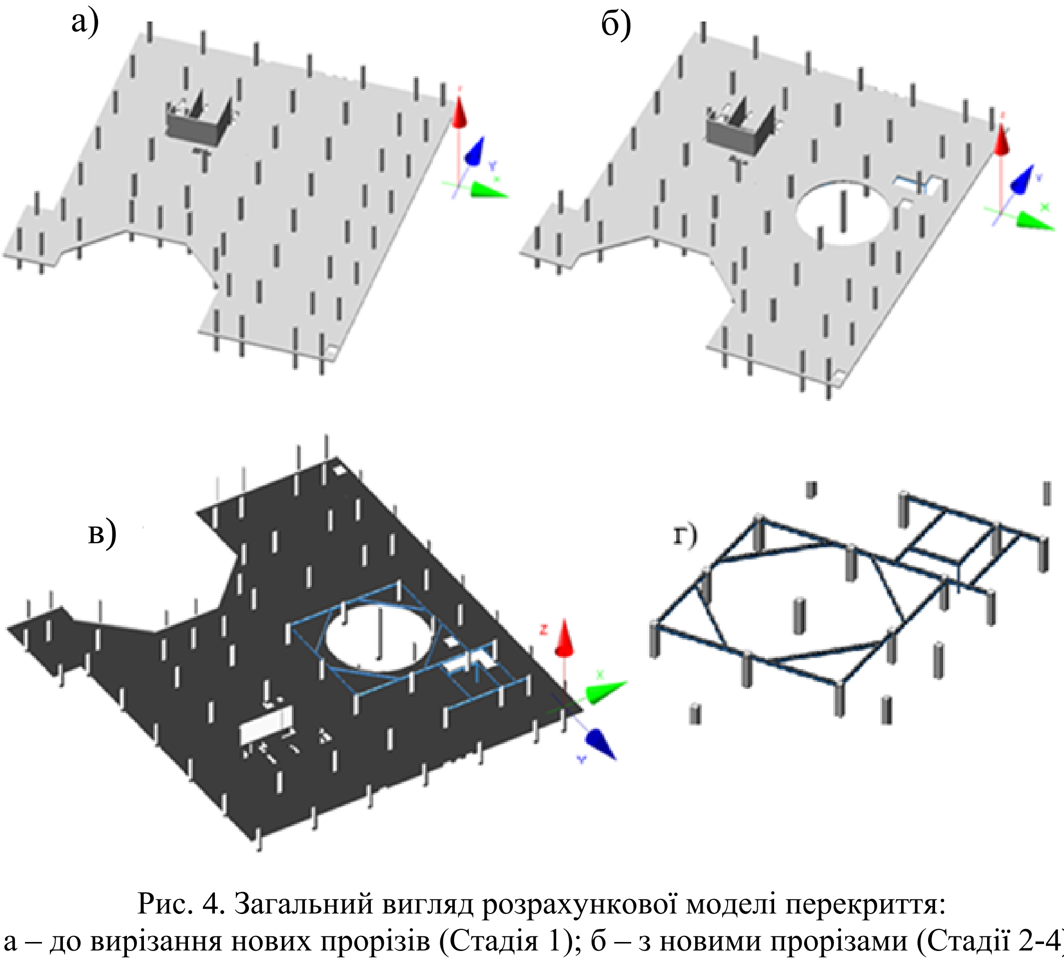

Рис. 4. Загальний вигляд розрахункової моделі перекриття:
а – до вирізання нових прорізів (Стадія 1); б – з новими прорізами (Стадії 2-4);
в – Стадії 2-4 – вид з низу; г – фрагмент конструкцій підсилення

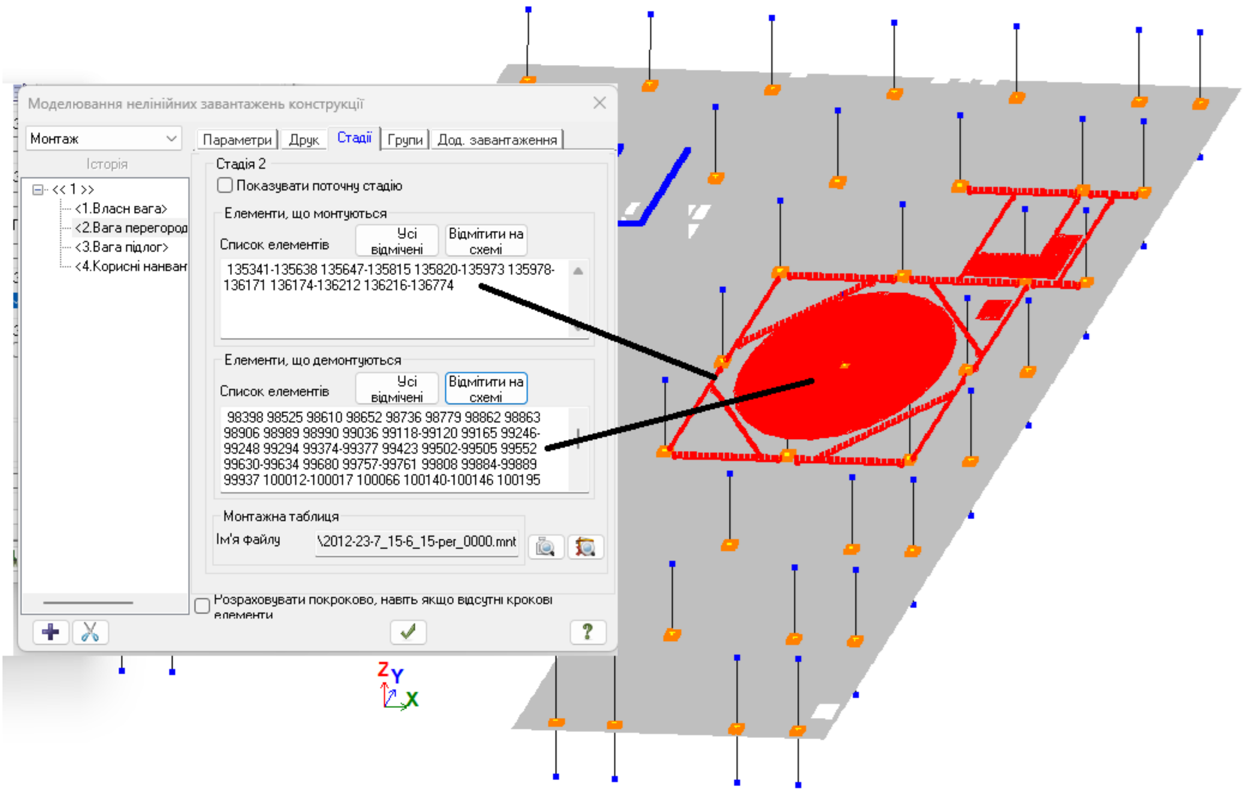

Рис. 5. Приклад вихідних даних до моделювання життєвого циклу конструкції в системі «Монтаж»

4. Характеристики жорсткості елементів моделі. Для залізобетонних елементів, які існують, характеристики жорсткості призначено з урахуванням фактичного армування. Для бетону прийнято залежність 15 – експоненціальний закон деформування для залізобетону (рис. 6). Для арматури залежність 11 – експоненціальний закон деформування (рис. 7).

Для сталевих балок підсилення попередньо прийнято прокатний двотавр 35Б1.

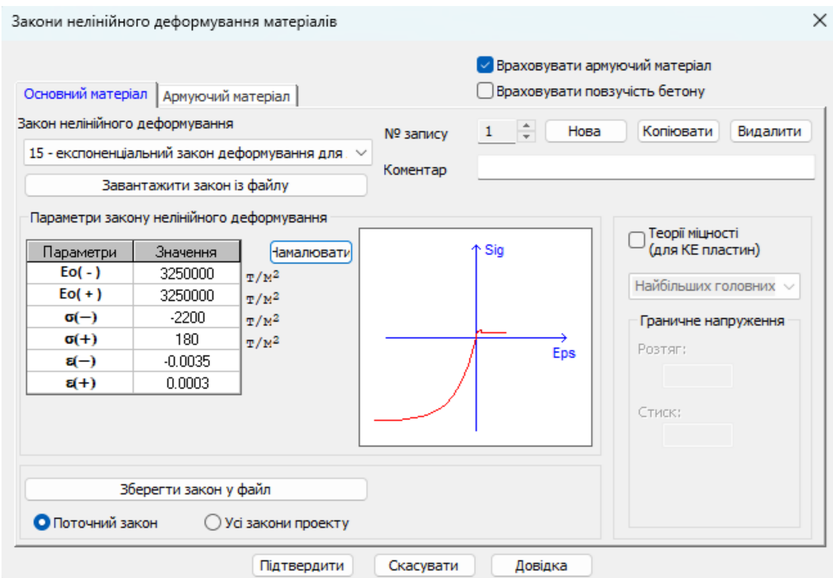

Рис. 6. Вихідні дані для врахування фізично-нелінійних властивостей бетону

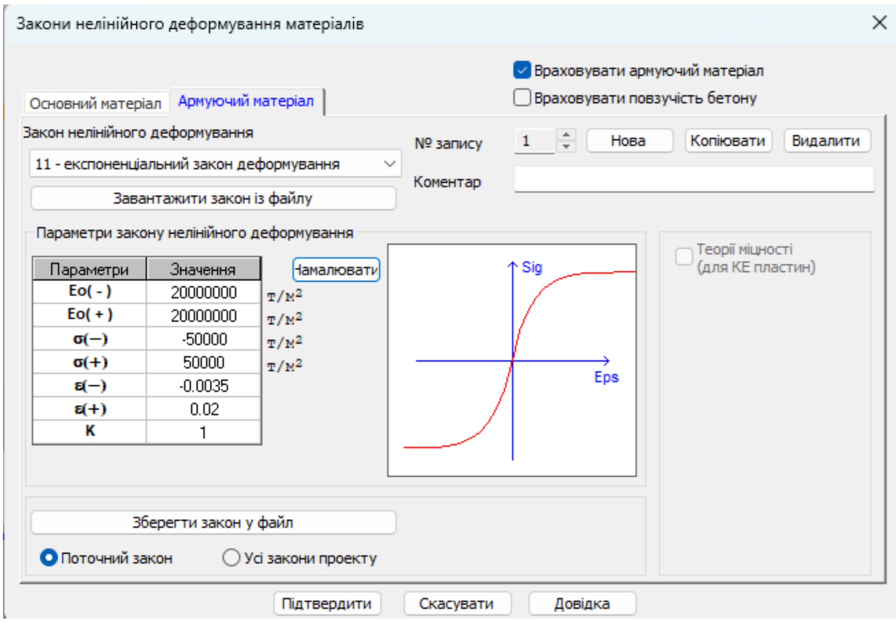

Рис. 7. Вихідні дані для врахування фізично-нелінійних властивостей арматури

Характеристики жорсткості односторонніх в’язей CE 262 визначаються наступним чином. Жорсткість елемента *R* є величина обернена його податливості. В даному випадку, податливість елемента буде дорівнювати абсолютній деформації стиску бетону Δ_c плити на верхньому поясі сталевої балки (рис. 8). При дії одиничної зосередженої сили N = 1 кН, для кожного вузла моделі податливість можна визначити за формулою:

$$\Delta_c = \frac{\sigma_c \cdot h_s}{E_c} = \frac{N \cdot h_s}{b \cdot S \cdot E_c} = \frac{1 \cdot 0{,}3}{0{,}155 \cdot 0{,}2 \cdot 3.25 \cdot 10^7} = 3.3 \cdot 10^{-6}\, м, \tag{1}$$

$$R = \frac{N}{\Delta_c} = \frac{1}{3{,}3 \cdot 10^{-6}} = 303030\, \frac{кН}{м}, \tag{2}$$

де σ – напруження в бетоні на верхньому поясі балки підсилення від одиничної сили; E_c – середнє значення початкового модуля пружності бетону; інші позначення – див. рис. 8.

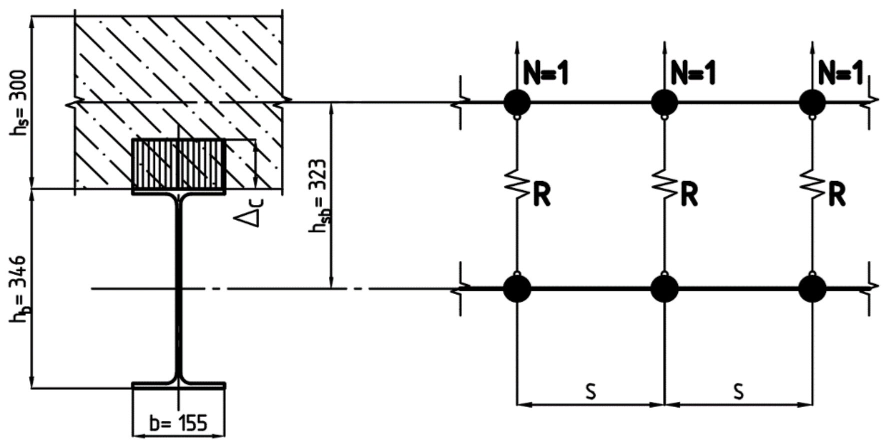

Рис. 8. До визначення жорсткості односторонніх в’язей CE 262

5. Аналіз результатів розрахунку. Для забезпечення механічного опору, стійкості та нормальної експлуатації конструкції, вона має бути перевірена за обома групами граничних станів. Перевірці підлягають наступні параметри:

– міцність з.б. конструкцій, що підсилюються;
– міцність і стійкість сталевих балок підсилення;
– прогини підсиленого перекриття;
– ширина розкриття тріщин в з.б. конструкціях.

На рис. 9 наведено зусилля в односторонніх в’язях на контакті «плита-балка». Як бачимо, в роботу включається тільки частина в’язей в зонах максимальних прогинів плити, що в цілому відповідає очікуванням (рис. 1, б). Кількість включених а роботу елементів в’язей, очевидно, залежить від жорсткості плити – чим менша жорсткість тим більше в’язей включиться в роботу.

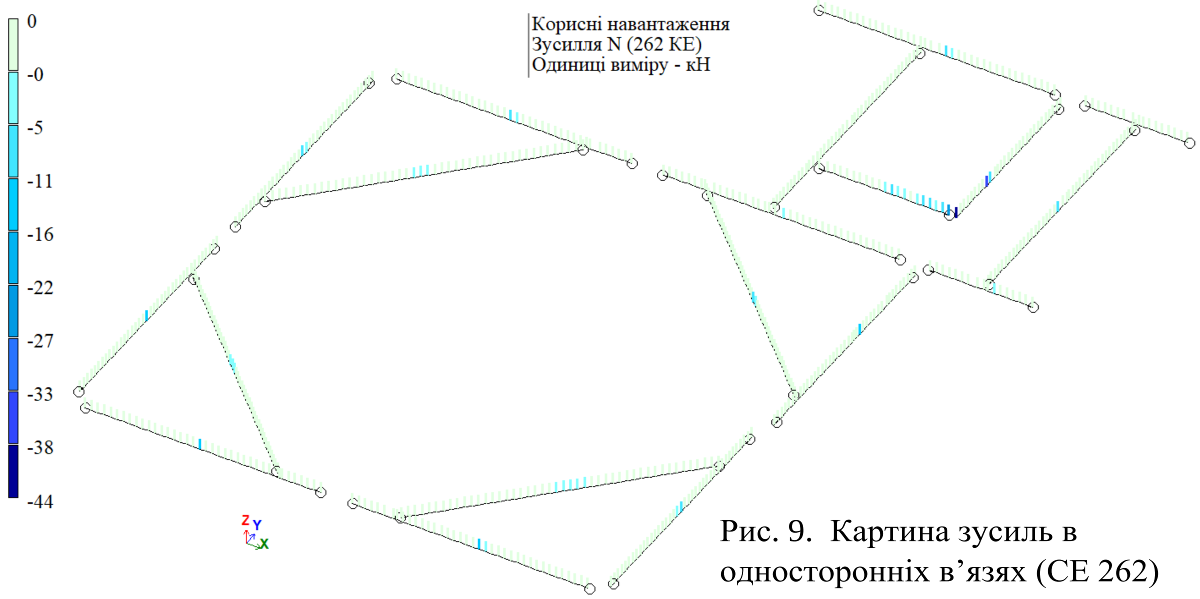

Рис. 9. Картина зусиль в односторонніх в’язях (СЕ 262)

При виконанні розрахунків в фізично-нелінійній постановці, ПК ЛІРА-САПР дає можливість візуалізувати руйнування конструкцій. На рис. 10 наведено картину руйнування моделі. Як бачимо, при врахуванні фактичного армування конструкцій повністю зруйновані елементи відсутні, ширина розкриття тріщин не перевищує вимог (0.3 мм) чинних норм [18].

На рис. 11 наведено прогини перекриття в зоні підсилення. Максимальний прогин 7+25 мм = 32 мм, що не перевищує вимог норм [22] (допустимий прогин 7900/216=36.6 мм).

На рис. 12 показані епюри зусиль в балках підсилення. В балках крім згинальних моментів виникають також повздовжні сили. Цей ефект добре відомий і описаний, наприклад, в [26, с. 208...214]. Тому балки підсилення слід розраховувати по [19] як позацентрово-розтягнуті або позацентрово-стиснуті елементи. На рис. 13 показано результат перевірки перерізів балок підсилення в модулі Сталеві конструкції ПК ЛІРА-САПР.

У випадку невідповідності розрахункових параметрів вимогам норм слід скоригувати схему підсилення (збільшити переріз балок, змінити схему їх розташування).

Висновки. Розроблено практичну методику розрахунку монолітних плит перекриттів, підсилених сталевими балками за допомогою ПК ЛІРА-САПР. Методика дозволяє виконувати розрахунки для забезпечення механічного опору, стійкості та нормальної експлуатації конструкції за обома групами граничних станів. Запропонований алгоритм розрахунку може бути адаптований і при проєктуванні підсилення збірних з.б. плит перекриття.

Наведена методика розрахунку застосувався автором при проєктуванні багатьох об’єктів, які були реалізовані і успішно експлуатуються вже тривалий час.

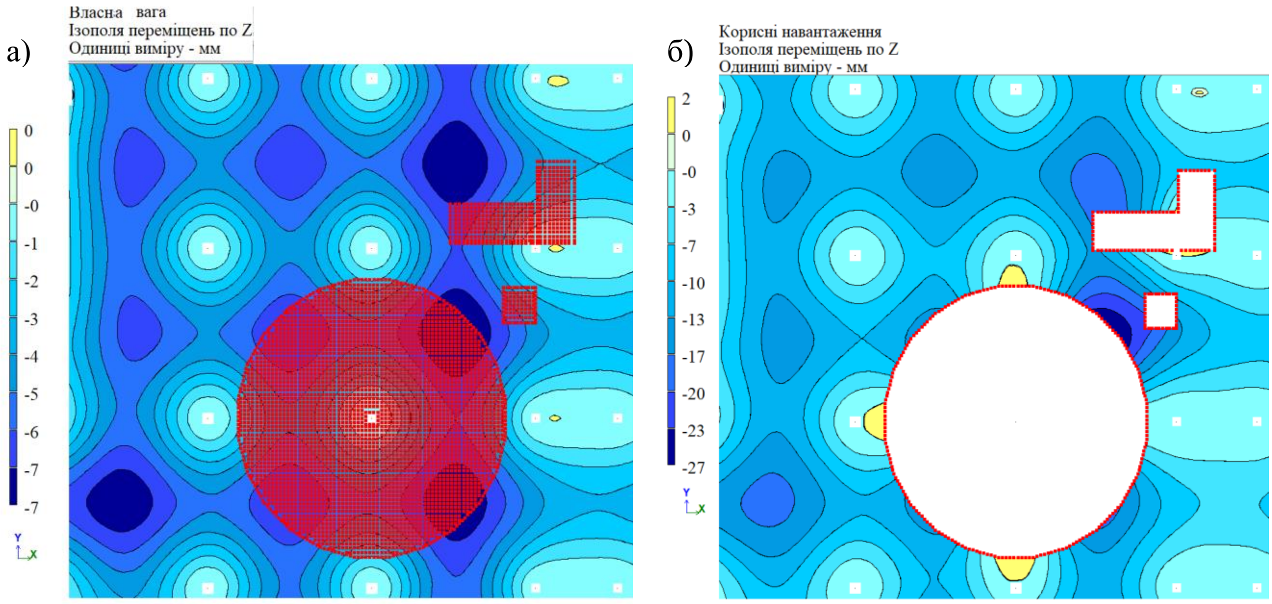

Рис. 11. Прогини підсиленого перекриття: а – прогини від власної ваги до підсилення (Стадія 1); б – прогини від експлуатаційних навантажень після підсилення і виконання нових прорізів (Стадія 4)

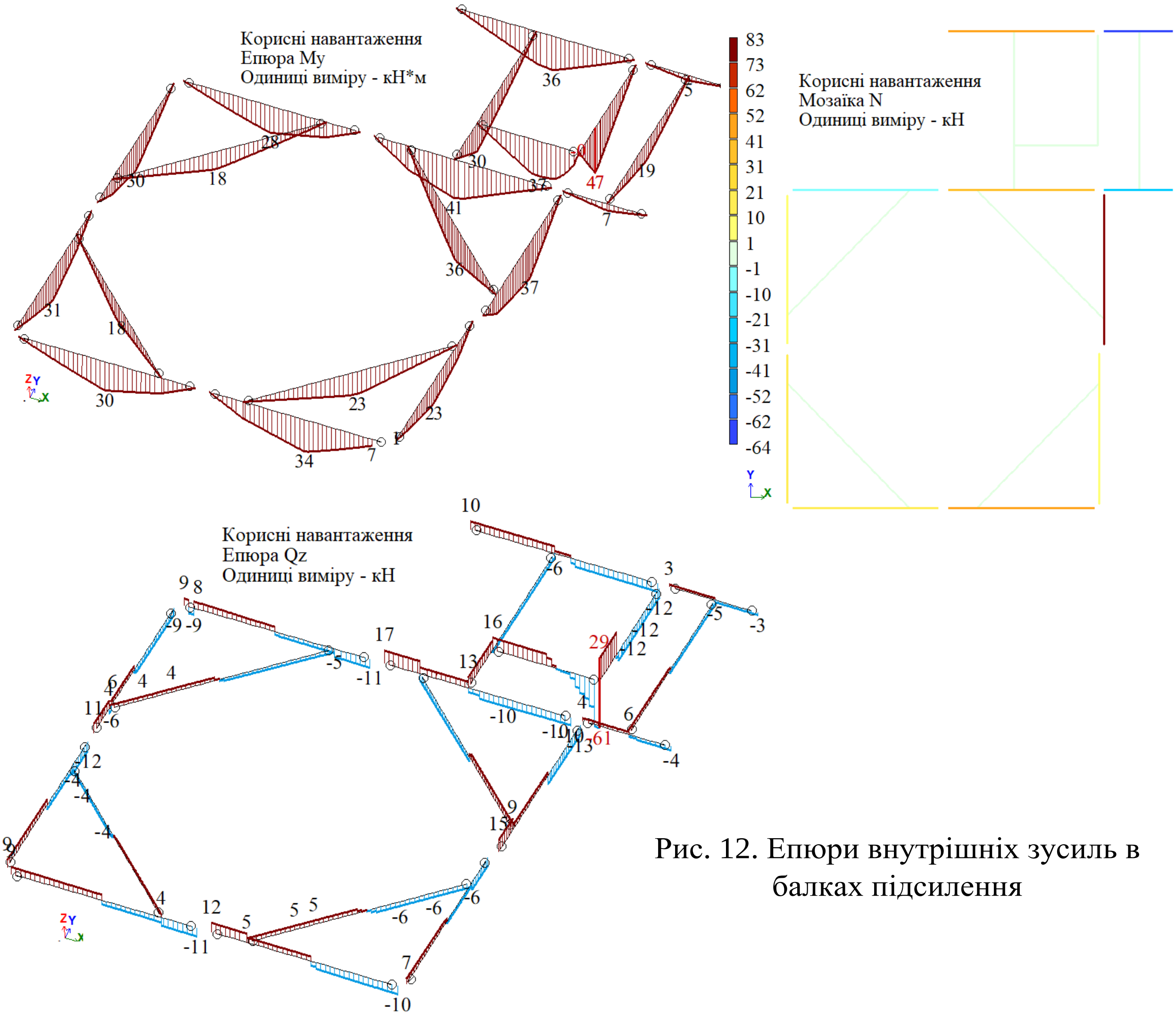

Рис. 12. Епюри внутрішніх зусиль в балках підсилення

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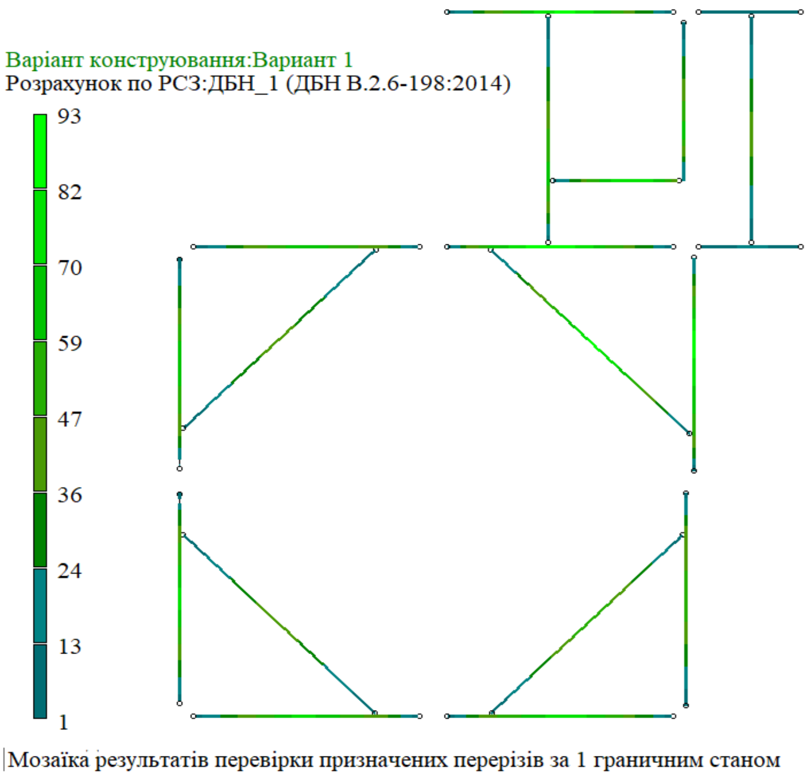

Рис. 13. До перевірки перерізу балок підсилення за першою групою граничних станів

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PRACTICAL METHOD FOR CALCULATION OF MONOLITHIC FLOOR SLABS STRENGTHENING WITH STEEL BEAMS

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Abstract. The method of strengthening of monolithic reinforced concrete slabs with steel beams in the lower zone is considered. From the late 1990s to the present, residential and civil construction in our country has been based on monolithic frame technology, where flat slabs are mainly used. Slabs often need to be strengthening as a result of damage caused by various reasons or when architectural and planning solutions are changed. Strengthening of such slabs with steel beams is used quite often in construction practice, especially in cases where it is not possible to fully unload the slab structure. The technical solutions for this method of strengthening have been developed for a long time and have many variations. However, if we analyse the building codes in the field of reconstruction and strengthening, we can identify a certain lack of calculation methods for the analysis of strengthening structures. A slab in a monolithic frame system is a repeatedly statically indeterminate structure, so its adequate calculation without the use of modern software systems is hardly possible.

A review of the current building codes in the field of reconstruction and strengthening is carried out. A number of publications in professional journals devoted to this topic and calculation approaches in the design of strengthening are considered. The structural features of strengthening with unloading beams are analysed. A practical methodology for calculating monolithic slabs strengthening with beams in the lower zone using the LIRA-SAPR software package is proposed. The methodology is based on taking into account the initial deformed state of the floor slab. The calculation is carried out by a step-iterative method, taking into account the physical-nonlinear properties of reinforced concrete and the life cycle of the structure. Particular attention is paid to the method of modelling the contact zone "slab-strengthening beam". The contact zone is modelled by means of one-sided connection, which perceives only compression forces.

The presented calculation algorithm has been tested by the author in the design of many facilities that have been implemented and successfully operated for a long time.

Keywords: floor slab, strengthening beam, model, calculation.

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ANALYSIS OF STRUCTURAL FAILURE MECHANISMS IN BUILDINGS SUBJECTED TO BLAST LOADS

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Abstract. This paper presents a comprehensive analysis of damage to buildings and infrastructure resulting from military actions, with a particular emphasis on modern conflicts and their devastating consequences. The primary focus is on a profound examination of various factors causing deformation and destruction: from the destructive effects of explosive shock waves and dynamic loads to mechanical impacts (shrapnel, direct hits) and intense thermal factors (fires, high-temperature exposures).The study encompasses a representative sample of over 150 structures of various types, located in active combat zones. This enabled a detailed examination of typical failure and degradation mechanisms in key structural systems, such as panel buildings, traditional brick masonry, monolithic and precast reinforced concrete structures, as well as lightweight frame and rapidly assembled constructions. Key findings confirm the empirically established pattern that the intensity of damage decreases exponentially with increased distance from the explosion's epicenter, which is crucial for hazard zoning. A significant correlation was also established between the nature of the consequences, the type of explosion (airburst, ground-level, subsurface), its power, and the structural features that determine a building's inherent resilience to external influences. To accurately assess the parameters of explosive waves, including their pressure, impulse, and duration, advanced methods were employed. These methods combine empirical formulas derived from field tests with high-precision numerical modeling using the finite element method (FEM). Based on the comprehensive analysis, a set of practical recommendations is proposed. They include the use of more durable, ductile, and energy-absorbing materials, the retrofitting and strengthening of existing buildings, and the optimization of urban planning solutions, considering principles of protective design and infrastructure dispersion. The objective of this work is not only to document and analyze damages but also to significantly improve existing methodologies for calculating structural responses to blast loads. Furthermore, the study investigated the impact of secondary factors such as collapses, ground deformations, and subsequent settlements, which often accompany primary destructions and exacerbate the overall condition of affected objects.

Keywords: structural damage, blast loads, building resilience, damage assessment.

Relevance and statement of the problem. Explosions, whether from military activity, industrial accidents, or terrorist attacks, present unique challenges for structural engineering. Buildings, often designed for static and wind loads, are not equipped to handle the dynamic pressures of explosive shock waves. This study synthesizes findings from Ukraine and other conflict zones, providing a comprehensive analysis of damage mechanisms and offering global solutions for improving building resilience.

The analysis of the technical condition of buildings and structures was conducted based on inspections of more than 150 objects.

The loads and impacts experienced by structures during military operations have unique characteristics, as the industrial and civil buildings were not originally designed to withstand the following effects and loads associated with military actions:

- the impact of explosion shock waves;

- mechanical damage caused by missile strikes, shell impacts, fragments, and debris;
- dynamic loads resulting from shock waves or structural vibrations;
- thermal effects caused by fires.

Analysis of recent research and publications. Drawing on the extensive data provided in recent reports and studies [1-4], this section outlines the key findings related to the types of damage sustained, the methodologies employed in assessing these damages, and the factors influencing the severity of destruction. Damage from Explosive Shock Waves. Direct Effects: explosive shock waves cause widespread cracking, displacement, and destruction of both load-bearing and non-load-bearing structures. The formation of cracks and spalling in concrete and masonry walls, particularly near the explosion epicenter [1, 4]. The complete collapse of prefabricated panel buildings when exposed to close-range aerial bomb strikes [3].

Indirect Effects: shock waves generate vibrations that weaken structural connections, leading to secondary failures such as the collapse of window frames and ceilings [2].

Mechanical Damage from Fragments and Projectiles. Penetration and Fragmentation: high-velocity projectiles, including shrapnel and bullet fragments, cause perforations in walls and structural elements. These effects are particularly severe in lightweight construction [3, 4] Thermal Effects from Fires. The thermal effects of explosions result in the elongation and weakening of steel reinforcements and the destruction of combustible elements such as wooden beams and roofs [4]. Dynamic Loads and Vibrations. Prolonged exposure to dynamic loads from repeated shelling leads to structural fatigue, affecting the overall stability of buildings even without direct hits [1, 4].

Damage Patterns by Building Type. Panel Buildings. Most vulnerable to direct explosive impacts due to weak connections between prefabricated panels. Damage includes the detachment of panels, extensive cracking, and partial or complete collapse [3]. Brick Masonry Structures. Characterized by cracks at the corners and intersections of walls. Delamination and spalling are common, with significant damage concentrated near the explosion epicenter [4]. Reinforced Concrete Structures. More resilient to shock waves but experience localized damage such as spalling and cracking in beams and columns. Progressive collapse is often mitigated by the redistribution of loads [1, 3]. Lightweight and Temporary Structures. Wooden and lightweight metal structures are the least resilient, with widespread destruction even at moderate distances from explosion epicenters [2, 4]. Factors Influencing Damage Severity. Distance from Explosion: The intensity of damage decreases exponentially with distance, with near-epicenter structures experiencing catastrophic failure [1, 3].

Explosion Type: Airbursts cause widespread but less intense damage compared to ground-level explosions, which produce concentrated pressure loads [4]. Obstacles and Building Orientation: the presence of adjacent structures or natural barriers influences the distribution of shock wave forces and can shield or amplify damage [3]. Structural Characteristics: buildings with high spatial rigidity, such as monolithic-frame constructions, demonstrate greater resistance to collapse [1, 4].

Buildings and structures are most commonly affected by explosion shock waves. An explosion shock wave is a specific type of disturbance that occurs in the surrounding medium during an explosion (caused by high explosives, dust, or gas). It is characterized by a sudden, abrupt increase in pressure accompanied by compression, heating, and changes in the velocity of the medium.

An explosion shock wave in the air represents the explosion's propagation surface, moving at speeds of 300 m/s or more. A visual example of an explosion shock wave in the air can be seen in Fig. 1.

An explosion shock wave creates a load along the front of its propagation. Typically, the load (pressure on the wave's surface) acts perpendicular to the vertical surfaces of a building (walls, windows, doors) and spreads at a high velocity [5].

Purpose and tasks. The purpose of this work is to develop new engineering solutions and design standards that will enhance the safety, resilience, and survivability of civilian infrastructure in the face of hybrid threats and military conflicts, by thoroughly analyzing damages and improving methodologies for calculating structural responses to blast loads. The main tasks are determined:

- to conduct a comprehensive analysis of damage patterns and typical failure mechanisms in over 150 structures of various types (panel buildings, brick masonry, reinforced concrete, lightweight

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constructions) subjected to military actions, focusing on the destructive effects of explosive shock waves, dynamic loads, mechanical impacts, and thermal factors;

Fig. 1. Formation and propagation of an explosion shock wave in the air

- to establish and quantify the correlation between damage intensity, distance from the explosion's epicenter, type of explosion (airburst, ground-level, subsurface), its power, and the inherent structural features that determine a building's resilience;
- to utilize and integrate advanced methods, including empirical formulas and high-precision finite element modeling (FEM), for accurately assessing explosive wave parameters and simulating complex interactions between blast waves and different structural systems, thereby predicting their response to various loading scenarios;
- to develop a set of practical recommendations for enhancing structural stability in existing and newly designed constructions under potential military threats, focusing on material selection (durable, ductile, energy-absorbing), retrofitting strategies, and optimized urban planning principles (protective design, infrastructure dispersion);
- to investigate the impact of secondary damage factors, such as collapses, ground deformations, and subsequent settlements.

Materials and methods of research. The research was carried out with the extensive use of systems analysis methods and statistical research, as well as field observations and detailed documentation of damaged structures. The study employed advanced analytical techniques, including empirical formulas derived from blast testing and high-precision numerical modeling using the finite element method (FEM) for simulating blast wave propagation and structural response. The proposed methods made it possible to identify, analyze, and build empirical and computational dependencies crucial for understanding damage mechanisms and proposing mitigation strategies.

The most severe damage caused by the shock wave affects the structures of external walls, including wall panels, brick masonry, enclosing structures, and transparent elements such as windows, skylights, gates, and doors[6].

The effect of air-based explosion shock waves on structures depends on the type of explosion: ground-level, airborne, or above-ground detonations. An air shock wave consists of two phases:

– Compression Phase, where the pressure exceeds atmospheric levels.

– Rarefaction Phase, during which the pressure drops below atmospheric levels (Fig.2).

The maximum pressure in the compression phase of an explosion shock wave significantly exceeds both atmospheric pressure and the pressure during the rarefaction phase. The key parameters of a shock wave propagating through the air from the explosion center are determined using empirical formulas [7, 8].

For an air explosion of a TNT charge [8]:

$$\Delta P_f = 0{,}084\frac{\sqrt[3]{c}}{R} + 0{,}27\frac{\sqrt[3]{c^2}}{R^2} + 0{,}7\frac{c}{R^3}, (\text{МПа}); \tag{1}$$

$$\tau_{(+)} = 1{,}5 \times 10^{-3}\sqrt[6]{c} \times \sqrt{R}, (c); \tag{2}$$

where c is the mass of the TNT charge (kg), and R is the distance from the explosion center (m) [9].

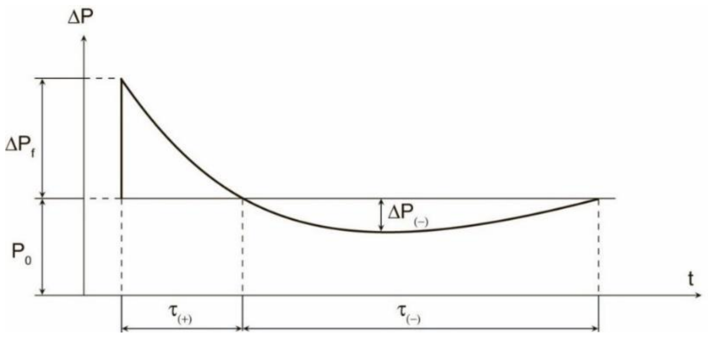

Fig. 2. Pressure variation graph along the front of the explosion shock wave

The change in pressure during the compression phase over time is determined by the following equation [8]:

$$\Delta P(t) = \Delta P_f \left(1 - \frac{t}{\tau_{(+)}}\right)^n, \quad 0 \leq t \leq \tau_{(+)}, \tag{3}$$

$$n = \Delta P_f \frac{\tau_{(+)}}{i} - 1, \qquad i = 6{,}3 \frac{\sqrt[3]{c^2}}{R}.$$

This corresponds to curve 1, shown in Figure 3 [10]. When calculating the effect of an air-based explosion shock wave on a structure, the linear dependence (line 2 in Figure 3) can be used as an alternative to equation (3).

$$\Delta P(t) = \Delta P_f \left(1 - \frac{t}{\Delta t}\right), \tag{4}$$

$\Delta t = \frac{2\tau_{(+)}}{n+1}$ – the effective duration of the shock wave, which is determined by the condition of impulse pressure equality.

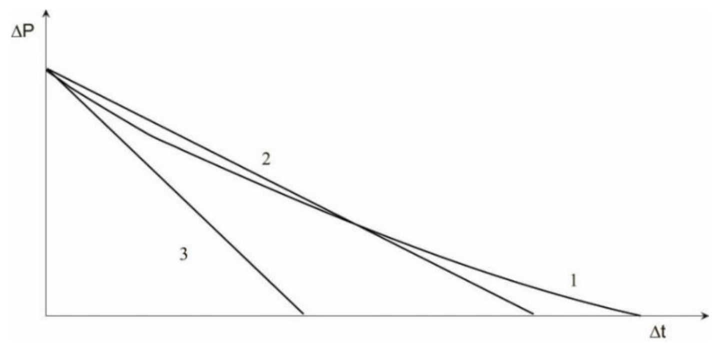

Fig. 3. Dependency of explosion pressure magnitude on time

The maximum reflection pressure ΔP_V, acting at the initial moment of time on a flat frontal obstacle perpendicular to the direction of wave propagation, reaches [8]:

$$\Delta P_V = 2\Delta P_f + \frac{6\Delta^2 P_f}{\Delta P_f + 0{,}72}, \tag{5}$$

and then decreases during the flow around the obstacle, according to the graph shown in Figure 4.

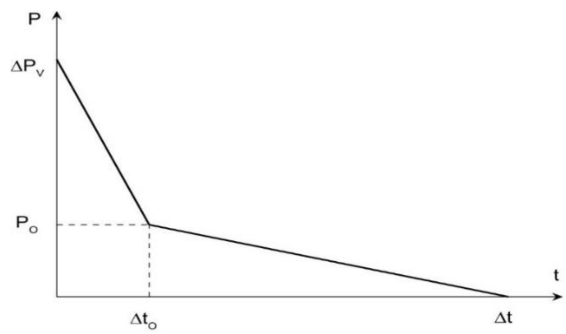

Fig. 4. Graph of the impact of the explosion shock wave on a building

The complete picture of the flow around the obstacle is shown in Figure 5.

The time ΔtO from the beginning of reflection to the onset of the flow-around regime:

$$\Delta t_O = \frac{3H}{D_f}, \tag{6}$$

Where H is the height of the frontal wall. (or 0,5b);$D_f = 340\left[1 + 8{,}3\Delta P_f\right]^{\frac{1}{2}}$, – and is the speed of the shock wave front.

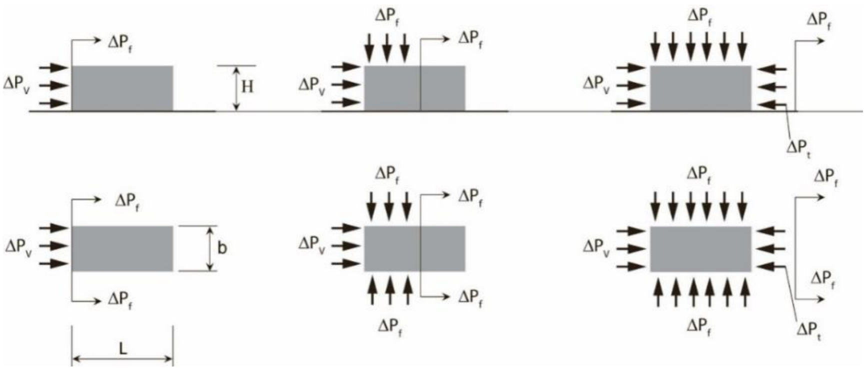

Fig. 5. Overall view of the impact of the explosion shock wave on the structure

When calculating the effect of explosive loads on structures, the actual laws of pressure variation over time are replaced with simplified ones, as shown in Figure 6.

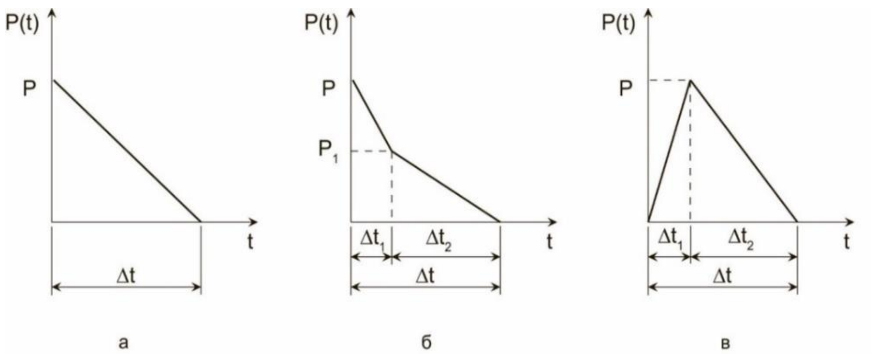

Fig. 6. Simplified laws of pressure variation over time

The load, the changes of which are shown in Figure 6, is used for calculating the roof and side walls (6a), frontal walls (6b), and the rear side of the structure (6c).

The functions used in the calculations depend on from $\Delta t\omega, \Delta t_1\omega, \Delta t_2\omega$,, where ω is the frequency of the natural vibrations of the structures [11].

If $t \geq \Delta t_1$or$\Delta t_2\omega \geq 50$, then during the calculation of the structure in the elastic stage, the load can be considered constant over time [12].

If the duration of the load is relatively short, such that$\Delta t\omega < \pi/2$, the structure can be calculated as being subjected to an instantaneous impulse.

$$I = \int_0^{\Delta t} P(t)dt. \tag{7}$$

If $\Delta t_1\omega \geq 20$, then the effect of the load on the structure will be equivalent to a static load P.

For engineering calculations of building structures subjected to air shock waves, simpler dependencies are used, as presented in works [1, 2], which allow for determining [8]:

$$\Delta P_f = 89{,}79\frac{r}{R} + 2204\left(\frac{r}{R}\right)^2 + 0{,}71;$$
$$\Delta P_V = \Delta P_f\,\frac{8\Delta P_f - 1}{\Delta P_f + 6}; \tag{8}$$
$$\Delta t = \frac{r}{D}\frac{6\Delta P_f + 1}{4\Delta P_f + 3},$$

$D_f = 306{,}7[\Delta P + 1{,}18]^{\frac{1}{2}}$–the velocity of the air shock wave;

$\Delta P = \Delta P_f - P_0; r = 0{,}062\left(\frac{c}{\gamma}\right)^{\frac{1}{3}}$–the average radius; γ– the specific weight of the charge.

Research results. During the analysis of structural damage caused by military operations, it was found that the damage to the structure occurs as a result of the air shock wave, mechanical damage from the delivery of explosive devices, and dynamic loads [13, 14].

The greatest damage from the shock wave is typically observed in the external walls of buildings, external wall panels of residential buildings, and transparent elements that are oriented perpendicular to the shock wave's propagation front.

It should be noted that as the explosion distance from the object increases, the speed and pressure of the shock wave at the front of the wave decrease significantly, inversely proportional to the square of the distance from the explosion's epicenter to the object. At a large distance, the shock wave degenerates into a sound wave.

The speed of propagation of the sound wave is lower than the speed of sound, but even at a speed exceeding 100 m/s, it causes significant damage to transparent elements (windows), roofing, and roof structures.

The shock wave in the ground quickly dissipates and cannot be considered as a factor of destruction. The fastest attenuation of the shock wave is observed in non-cohesive soils. Even at small distances from the explosion (within 6–10 meters), the foundations of buildings experience almost no damage, except in cases where the explosive device directly hits the upper part of the foundation.

Building damage also occurs due to mechanical destruction caused by the impact of explosive delivery devices (Figure 7).

Fig. 7. Mechanical destruction of building structures in the elevator shaft by an explosive delivery device (the explosive device did not detonate)

The greatest damage to the building's structure occurs as a result of the simultaneous impact of the explosion shock wave and the mechanical action of the explosive delivery device (Figure 8).

Fig. 8. Panel building structures damaged as a result of the explosion shock wave and the impact of the explosive delivery device (the explosion occurred inside the building)

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Significant damage occurs in the structures of lightweight concrete wall panels and self-supporting external wall structures (brick masonry, ceramic block masonry). These structures have relatively low mass and low inertia, which is why they respond quickly to excitation. Panel buildings, in which external wall panels and ceiling slabs are made of heavy concrete, are more resistant to the effect of the shock wave.

It should be noted that panel buildings with load-bearing external and internal transverse walls have quite high spatial rigidity, especially buildings with a square floor plan (for example, single-section 16-story panel buildings).

If the explosive device detonates inside the building, the shock wave propagation affects the structure from the inside. Significant damage from such explosions occurs to the external enclosing structures, leading to their collapse and the destruction of parts of the building (Figure 9).

Monolithic-frame buildings exhibit the highest resistance to the effects of explosion shock waves. Significant damage typically occurs in non-load-bearing enclosures and partitions. The building’s frame elements, pilasters, columns, and monolithic slabs experience defects such as chips and cracks. In powerful explosions, the structural frame elements undergo destruction. However, the forces in the frame elements are redistributed, preventing progressive collapse.

Frame buildings (reinforced concrete, steel, or mixed-frame structures) suffer damage in the form of concrete spalling, cracking, and deformation. In large explosions, individual structural elements collapse. In single-story industrial buildings, separate ceiling panels, beams, and trusses may collapse. Fragmentation damage affects ceiling panels, beams, trusses, and columns. There may also be damage to the joints, but this usually does not lead to the overall collapse of the building.

Fig. 9. Destruction of the building's structure due to an explosion inside the building

In buildings with a steel frame, explosions cause significant deformations, bending, and rupture of elements. In intense explosions, the cross-sections of metal elements, the frame, connection joints, welds, bolts, and the formation of through holes in the metal structures may be destroyed. Major explosions can lead to the collapse of trusses, purlins, and roof structures (Figure 10).

Fig. 10. Destruction of metal structures of the roof in an industrial building

In the case of powerful internal explosions, significant or complete destruction of the external enclosing structures occurs, while the frame elements are preserved (Figure 11).

Fig. 11. Destruction of the external enclosing structures of a frame building due to an internal explosion

In panel buildings, depending on the location of the impact zone and the explosion's strength, cracks, chips, significant deformations, and destruction occur in the walls. Significant linear or angular displacements arise at the junctions of the panels, weld seams, anchoring details fail, and stretching or destruction occurs in the connecting metal elements. In large explosions, the collapse of wall structures, floors, balconies, and staircases within the structural blocks (sections) may occur (Figures 12).

Brick walls of buildings, due to significant kinetic impact from the delivery of explosive devices, suffer damage in the form of holes in the structures, chips, cracks, and delamination of the masonry. Significant vertical cracks develop at the corners of walls and at their intersections, leading to the separation of sections of walls and a substantial reduction in their spatial rigidity. Wooden floor structures in brick buildings experience significant damage and destruction over several floors. The destruction of reinforced concrete slabs is more limited, resulting in cracks and significant deformations. In the case of large explosions, the destruction of external walls leads to the complete collapse of floor slabs (Figure 12).

Fig.12. Destruction of floor slabs, wall panels, and panel connection joints in a residential building

In brick buildings with a wooden truss roof system, explosions within the attic lead to partial or complete destruction of the truss system and roof. The collapse of destroyed elements occurs on the roof slab or, if it is also destroyed, on the inter-floor slab structure (Figure 13).

Buildings with wooden load-bearing walls, wooden floor structures, and wooden roofs, when subjected to minor explosions, experience defects and damage in the form of cracks, destructions, and significant deformations of the entire structure, typically rendering them unfit for further use.

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Fig. 13. Damage to wooden roof structures caused by the explosion shock wave

Conclusion. Explosive shock waves present unique and severe challenges to structural integrity, particularly in conflict zones. Empirical studies from Ukraine, the Middle East, and other regions reveal consistent patterns of damage and highlight the importance of engineering innovations. Proactive design, retrofitting, and urban planning can significantly mitigate risks, protecting lives and infrastructure worldwide.

1. Material Advancements. Ultra-High-Performance Concrete (UHPC): Provides superior resistance to compressive forces. Blast-Resistant Glass: Reduces injuries and secondary damage from glass fragmentation.

2. Structural Reinforcements. Cross-bracing and shear walls improve stiffness and distribute dynamic loads. Enhanced connections between structural components reduce progressive collapse risks.

3. Urban Planning. Zoning regulations should ensure adequate distances between industrial facilities and residential areas. Protective barriers and blast walls can shield critical infrastructure.

4. Advanced Computational Tools. Finite Element Analysis (FEA) allows engineers to model blast impacts accurately, identifying failure points and optimizing designs for blast resistance.

Recommendations for Global Applications [15]:

– Standardized Blast-Resistant Codes: International guidelines should integrate findings from conflict zones to develop robust building standards [15].

– Retrofitting Existing Infrastructure: Governments and engineers should prioritize retrofitting critical buildings with blast-resistant technologies.

– International Collaboration: Sharing data from conflict zones, such as Ukraine and Syria, can advance global engineering practices and save lives in future scenarios.

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АНАЛІЗ МЕХАНІЗМІВ РУЙНУВАННЯ БУДІВЕЛЬНИХ КОНСТРУКЦІЙ ПРИ ВИБУХОВИХ НАВАНТАЖЕННЯХ

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Анотація. У цій статті представлено всебічний аналіз пошкоджень будівель та інфраструктури, що сталися внаслідок військових дій. Основна увага зосереджена на вивченні різноманітних факторів, що спричиняють деформації та руйнування: від руйнівних ефектів вибухових ударних хвиль та динамічних навантажень до механічних ударів (уламки, прямі влучення) та інтенсивних термічних факторів (пожежі, високотемпературні впливи). Дослідження охоплює репрезентативну вибірку з понад 150 споруд різного типу, розташованих у зонах активних бойових дій. Це дозволило детально вивчити типові механізми руйнування та деградації в ключових конструктивних системах, таких як панельні будівлі, традиційна цегляна кладка, монолітні та збірні залізобетонні конструкції, а також легкі каркасні та швидкомонтовані споруди. Ключові висновки підтверджують емпірично встановлену закономірність, що інтенсивність пошкоджень експоненціально зменшується зі збільшенням відстані від епіцентру вибуху, що має вирішальне значення для зонування небезпеки. Встановлено значну кореляцію між характером наслідків, типом вибуху (повітряний, наземний, підземний), його потужністю та конструктивними особливостями, що визначають притаманну стійкість будівлі до зовнішніх впливів. Для точної оцінки параметрів вибухових хвиль, їх тиску, імпульсу та тривалості були використані передові методи, що поєднують емпіричні формули та високоточне чисельне моделювання методом скінченних елементів (МСЕ). На основі проведенного аналізу запропоновано комплекс рекомендацій, спрямованих на підвищення стійкості існуючих та проєктування нових конструкцій в умовах потенційних військових загроз. Ці рекомендації включають використання більш міцних, пластичних та енергоємних матеріалів, модернізацію та посилення існуючих будівель. Метою цієї роботи є не лише документування та аналіз пошкоджень, а й суттєве вдосконалення існуючих методик розрахунку реакції конструкцій на вибухові навантаження. Це дослідження є важливим внеском у розробку нових інженерних рішень та стандартів проєктування, що сприятимуть підвищенню безпеки та живучості цивільної інфраструктури в умовах гібридних загроз та військових конфліктів.

Ключові слова: пошкодження конструкцій, вибухові навантаження, стійкість будівель, оцінка пошкоджень.

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RESEARCH ON THE PROPERTIES OF SILICATE COMPOSITES FOR OPEN-ENVIRONMENT OBJECTS

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Abstract. The article presents a comprehensive study of the properties of silicate composites and materials based on them, aimed at substantiating the feasibility and effectiveness of their application in the field of landscape architecture for open-air objects. In particular, attention is focused on the possibilities of integrating such materials into the processes of spatial organization of parks and recreational areas, which is an urgent task of modern urban planning. The study considers key aspects that determine the operational potential of silicate composites, including their structural and technological characteristics, indicators of durability, environmental safety and aesthetic appeal.

Special emphasis is placed on the analysis of the potential use of silicate composites in the creation of small architectural forms, decoration of open spaces, as well as in the formation of functional components of the urban environment. The presented advantages of these materials in the context of modern construction demonstrate their ability to provide not only architectural expressiveness and functionality of objects, but also to reduce financial costs for their construction, further operation and maintenance.

The article emphasizes the importance of using environmentally friendly raw materials in the production of silicate composites, which contributes to reducing the negative impact on the environment and complies with the principles of sustainable development in architectural practice. The study includes calculations and analysis of experimental and statistical models that demonstrate the relationship between the structural parameters of materials and their operational characteristics.

In particular, detailed studies of such physical and technical indicators as compressive strength, frost resistance, water resistance, density, crack resistance and carbonization resistance were carried out. A comprehensive analysis of these criteria allowed us to draw reasonable conclusions regarding the prospects for the use of silicate composites in the design of architectural elements of the environment, landscape design for open-air facilities and the rational organization of outdoor spaces in modern urban conditions.

Keywords: silicate composites, properties, landscape design, open environment, ecology, experiment.

Introduction. In modern landscape design, there is a growing need to use innovative materials that combine high performance characteristics with aesthetic and environmental requirements. One of the promising groups of such materials is silicate composites, which attract attention as a potentially effective alternative to traditional materials. Despite the diversity of silicate composites, their integration into landscape design practice is still not sufficiently structured and widely implemented. This necessitates a comprehensive study of the properties and performance of silicate composites to substantiate their potential for practical application.

Analysis of recent research and publications. In recent years, there has been an increase in scientific interest in the use of silicate composites in the fields of construction, architecture and outdoor space design. A significant part of the research is focused on the physicochemical characteristics of silicate composites, their durability, resistance to aggressive environments, frost resistance and ability to maintain operational properties under prolonged load conditions [1, 2].

Works by domestic and foreign researchers focus on the potential of using various building composites in landscape design, in particular as materials that combine decorative properties with high resistance to atmospheric influences, environmental safety and the ability to integrate into the natural and architectural environment [3-5]. Special attention is paid to the modification of composites with the addition of nanomaterials, which allows to increase their strength, water resistance and heat resistance [6-8].

At the same time, in the field of landscape architecture, publications dedicated to the use of silicate composites remain rare [9]. In the available works, the emphasis is mainly on the decorative qualities and properties of materials, the possibilities of their use for decoration, cladding and creation of small architectural forms [10, 11].

Considering that recently in the construction industry there has been a tendency to use "green" ecological technologies that do not harm the environment and health, the requirements for building materials are increasing every year [6]. The prospects for using silicate composites in landscape design are offered by their unique operational properties, environmentally friendly and high aesthetic potential, which allows for the effective integration of these materials into the formation of a harmonious external environment. Due to their mineral base and the number of environmentally harmful components, silicate composites meet modern requirements for environmental safety and sustainable development of urban areas [10]. Of particular interest is the use of silicate composites in the creation of small architectural forms – benches, park furniture, decorative steles, flower pots, flowerpots and other elements of landscape design. Due to their stable structure, resistance to atmospheric influences, as well as wide possibilities for varying texture, color and shape, these materials contribute to the formation of visually attractive and durable objects of the urban and natural environment. The mechanical strength, wear resistance and frost resistance of these materials ensure the preservation of the functional and aesthetic characteristics of the surface even under conditions of intensive use [11].

Despite the fact that information about the degree of environmental friendliness of certain materials is currently insufficient, currently in construction, conditionally ecological materials are widely used, which include natural resources, are safe for the environment, but have high technical and operational characteristics. An example of such a material today can be environmentally friendly silicates and blocks based on them [6, 12]. They are made from natural environmentally friendly materials, which are distinguished not only by their environmental friendliness and accessibility, but also by the relatively low cost of the finished product. In addition to the fact that this material corresponds to the so-called green construction, its use will allow to reduce the weight of structures, increase the factory readiness of silicate blocks while reducing their specific energy consumption, and improve thermal characteristics. Compared with the production technologies of other building materials, the production of ecological silicates is energy and resource-saving, since the casting technology is used in combination with complex activation [12]. Ecological silicates and products based on them, due to their cost-effectiveness and properties, will be relevant not only for individual construction, but also for the creation of small architectural forms and can even be recommended for decorative elements of garden and park architecture and interior design [13-15].

Problem statement and research objective. In modern conditions, there is a growing need for environmentally safe, durable and aesthetically attractive materials for the arrangement of open public spaces, in particular park and recreational areas, pedestrian zones and landscaping objects. At the same time, existing materials do not always provide the proper balance between operational characteristics, economic feasibility and architectural and artistic expression. In this context, research into new materials, in particular silicate composites, which have the potential to be used in the formation of small architectural forms and other elements of the external environment, is relevant. However, for the justified introduction of such materials into design practice, it is necessary to carry out a comprehensive study of their properties, including mechanical, weatherproof, environmental and aesthetic characteristics, as well as to identify the dependencies between the structural parameters of composites and their effectiveness in open environment conditions.

Materials and methods of research. To achieve the set goal, it is necessary to analyze the patterns of the influence of the composition of the mixture and additives on the properties of silicate composites and develop optimal compositions of complex-activated silicates of thermal-moisture hardening with improved properties for use in landscape design. Accordingly, the subject of the study is silicate composites of thermal-moisture hardening. Experiments and research, which were carried out with the aim of building experimental and statistical models, were performed in several scientific laboratories of the Odesa State Academy of Civil Engineering and Architecture: determination of basic properties – by standard methods, as well as determination of structural characteristics – at the departments of "Building Materials", "Production of Building Materials and Structures" and "Processes and Devices in the Technology of Building Materials" [4, 6, 12, 16]. The processing of experimental and statistical models was carried out by means of the COMPEX dialog system in combination with specially synthesized planning approaches, standard Microsoft Office applications, and the CorelDRAW software environment.

To address the stated problem, experimental studies were conducted using identical 6-factor, 24-point experimental designs of the "triangles on a cube" type (Fig. 1), developed by Professor T.V. Lyashenko [17, 18]. These designs allowed for the simultaneous consideration of three independent and three dependent compositional parameters. To facilitate data analysis, the six-factor space was transformed into a three-factor framework by fixing the dependent variables at discrete levels while varying the three independent variables. Specifically, the specific surface areas of slag and sand were maintained at three fixed levels of 400, 500, and 600 m^2/kg. At each combination of dependent variable levels, the independent factors-dosages of alkaline additives (0.5–1%), liquid glass (1–5%), and gypsum (2–4%) – were systematically varied. Superplasticizer C-3 was applied at 1.0% of the binder mass to enhance sedimentation stability. Gypsum, as a key active component of the lime-silica mixture, played a dual role: it improved mixture mobility and contributed to the development of essential performance properties in the hardened composites. By adjusting the quantitative ratio of the initial components, it was possible to regulate the structure and properties of heat-moisture curing silicate composites, while controlling the influence of the fixed dependent parameters.

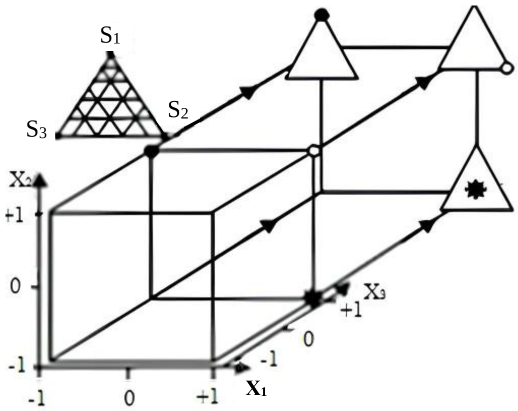

Fig. 1. Scheme of the plan "triangles on a cube"

The results of the research. In the experimental program, the assessment of silicate composites was carried out on the basis of a set of essential quality indicators established by current regulatory and technical documentation. These included compressive strength (R_{st}), frost resistance (F), water resistance (k_s), density (ρ), and the crack resistance coefficient (k_{Ic}). The analysis of the obtained results enabled a detailed evaluation of the material performance for each specified parameter.

The change in compressive strength under the influence of the studied factors, in particular the content of additives and the specific surface area of the silica-containing component, was described by a model, on the basis of which graphs of the dependence of compressive strength were constructed. Within the factor space, depending on the variation of all factors, the R_{st} indicator changed from R_{min} = 12.3 to R_{max} = 18.1 MPa (Fig. 2). The highest strength value was obtained for compositions with the maximum content of all additives.

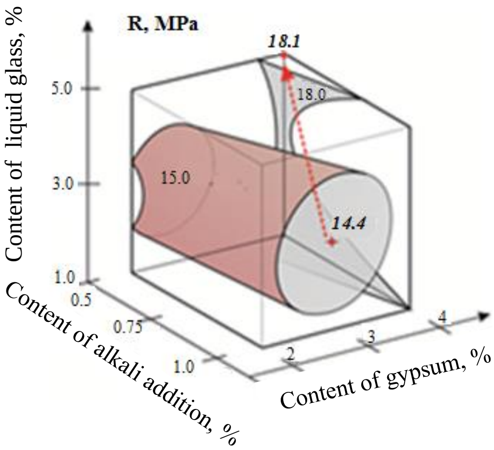

Fig. 2. Influence of all factors on compressive strength

Within the same area of the factor space (Fig. 3), the density value varies from 1340 to 1540 kg/m³, with the lowest density observed at minimum contents of gypsum and alkaline additives in the mixture. Such a density range is particularly suitable for landscape architectural elements, as it ensures a balance between mechanical strength and reduced self-weight. Lower-density composites allow for easier handling, transportation, and installation of items such as benches, decorative steles, planters, and park furniture, while still providing sufficient structural integrity and durability for landscape application.

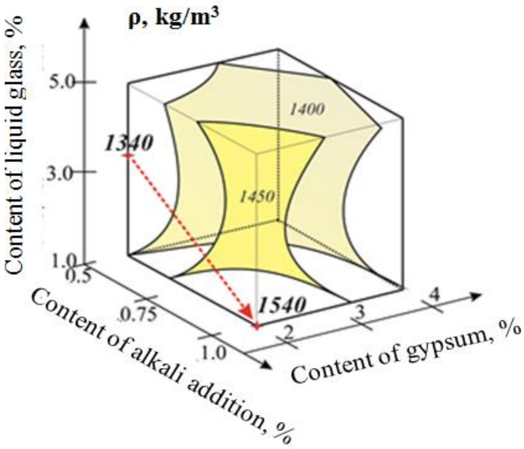

Fig. 3. Influence of all factors on density

In a similar way, diagrams of changes in properties were constructed according to frost resistance, which indirectly characterizes the durability of building materials (Fig. 4), and water resistance (Fig. 5).

Within the investigated factor space, the frost-resistance values (F) range from 26 to 33 cycles. It has been established that varying the specific surface area of the silica-containing component makes it possible to achieve standardized frost-resistance levels F25 and F35, which may be classified as sufficient for the operation of materials in environments with moderate freeze–thaw exposure, particularly in southern warm regions, where the number of natural freeze–thaw cycles is statistically low and the duration of periods with sub-zero temperatures is significantly reduced. The obtained indicators allow the use of the material in constructions that are not subjected to substantial mechanical loading and are characterized by limited water saturation. Examples of such applications include decorative garden and park elements (steles, sculptural forms, and other small architectural objects), components of park furniture located under partial shelter, planters and flowerpots with regulated drainage, as well as modular decorative blocks and inserts integrated into pavements in areas with minimal moisture exposure and without pedestrian or vehicular loading.

Water resistance was estimated by the softening coefficient, which in the studied factor space varied from 0.8 to 1.0. Due to the change in the studied factors, the softening coefficient can vary within 15–30%. All studied compositions provide water-resistant lime-silica composites. The highest water resistance, which is 0.9–1.0, is observed in compositions with a specific surface area of tripolite S_2 = 400 m²/kg.

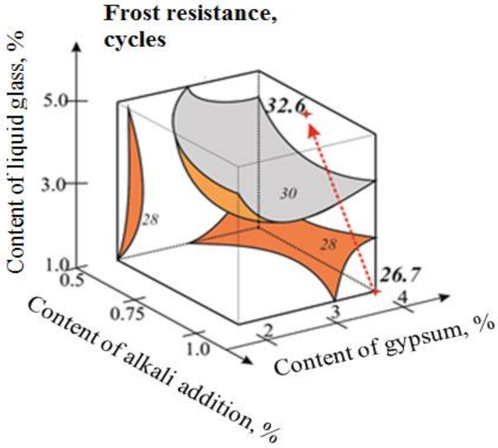

Fig. 4. The influence of all factors on the change in frost resistance

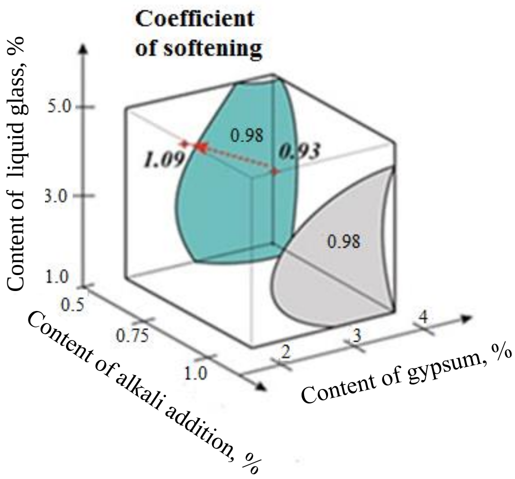

Fig. 5. The influence of all factors on the softening coefficient

In the experiment, the crack resistance of silicate composites was characterized by the critical stress intensity coefficient k_{Ic}, which, under the influence of all factors, changes by a factor of 1.8, from 0.91 to 1.64 MPa·m$^{-0.5}$ (Fig. 6). At the same time, the specific surface area of the silica-containing component has the greatest influence on the crack resistance.

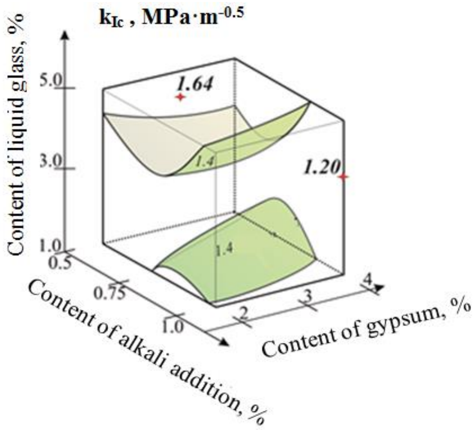

Fig. 6. The influence of all factors on the critical stress intensity coefficient

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One of the key factors in ensuring the durability of structural elements in landscape design is the resistance of the materials used to carbonization. Silicate composites are exposed to prolonged exposure to atmospheric factors, in particular carbon dioxide. As a result of carbonization, the pH of the material decreases, which leads to the destruction of the microstructure, a decrease in mechanical strength and the appearance of defects on the surface of the products. In view of this, a study of the carbonization resistance of the used silicate composites was conducted, which is a necessary prerequisite for predicting the operational reliability of landscape architecture elements.

The carbonation resistance of silicate composites of thermal and moisture hardening significantly depends on the content of active additives, in particular, liquid glass, alkaline components and gypsum. An increase in the amount of liquid glass helps to compact the microstructure of the composites, reducing their gas permeability, which has a positive effect on carbonation resistance. A similar effect is observed with an increase in the concentration of alkaline additives, due to the stabilization of the high alkalinity of the pore environment, which slows down the processes of carbon dioxide corrosion. Gypsum plays a dual role: with rational dosages, it helps to optimize the structure of the material, but its excess can lead to the appearance of microcracks that reduce carbonation resistance. Thus, ensuring high resistance of silicate composites to carbonation is possible due to the balanced selection of the composition with the optimal content of liquid glass, alkali and gypsum. The use of materials with high resistance to carbonization allows you to minimize the risks of premature destruction, reduce the costs of maintenance of landscaping objects, and preserve their aesthetic properties throughout their entire service life.

Adjusting the properties of the silicate mixture ensures the production of silicate materials and products based on them using energy-saving technology with improved properties of standardized grades in terms of density, strength, frost resistance, crack resistance coefficient, taking into account carbonation resistance. The following intervals of property changes were obtained: concrete class B7.5–15, ρ = 1150–1500 kg/m^3, k_s = 0.9–1, F≥35, k_{1c} = 0.91–1.64 MPa·m$^{-0.5}$, in connection with which silicate composites are recommended for use in landscape architecture (Fig. 7).

In the context of forming functional components of urban space, silicate composites can serve as an effective structural material for creating protective screens, urban barriers, lighting and landscaping elements that not only meet safety standards, but also harmoniously fit into the overall concept of spatial design. In the future, it is advisable to expand the research of these composites in order to increase their adaptability to different climatic zones, expand design possibilities and ensure maximum environmental neutrality.

Fig. 7. Examples of the use of silicate composites in landscape architecture

Conclusions. Based on the conducted research, it was established that silicate composites are promising materials for use in the field of landscape architecture, in particular in the formation of elements of park and recreational spaces, pedestrian infrastructure and small architectural forms. The experimental data obtained confirmed the high strength, resistance to atmospheric influences, wear resistance and environmental safety of these materials, which meets modern requirements for the organization of a comfortable and harmonious external environment.

A comprehensive analysis of physical and technical characteristics demonstrated that silicate composites are able not only to ensure the durability of structural elements, but also to contribute to aesthetic diversity in the design of urban space due to the wide possibilities of variation in shape, texture and color. Taking into account the results obtained, the use of silicate composites can be recommended for expanding the range of materials in landscape architecture design practice in order to improve the quality of the environment and reduce operating costs throughout the life cycle of objects.

The current tasks of further development of silicate composites for landscape architecture are to increase their strength, frost resistance, weather resistance and moisture resistance. Another important task is reducing the thermal conductivity of materials, as this helps regulate microclimatic conditions, prevents excessive surface heating, protects plants and soil, increases durability, and reduces the intensity of urban heat islands. Increasing the strength will allow creating landscaping elements that are more resistant to mechanical loads, in particular small architectural forms, garden and park structures, decorative fences and coatings. Improving frost resistance and moisture resistance will ensure the durability of products in various climatic conditions, including regions with difficult winter-spring operation. The color of the final product remains an important aspect for shaping the aesthetics of the landscape environment, therefore one of the areas of work is the study of additives that allow varying the color range of products without losing their basic physical and mechanical properties.

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ДОСЛІДЖЕННЯ ВЛАСТИВОСТЕЙ СИЛІКАТНИХ КОМПОЗИТІВ ДЛЯ ОБ'ЄКТІВ ВІДКРИТОГО СЕРЕДОВИЩА

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Анотація. У статті представлено комплексне дослідження властивостей силікатних композитів та матеріалів на їх основі, спрямоване на обґрунтування доцільності та ефективності їх застосування в галузі ландшафтної архітектури для об'єктів відкритого типу. Зокрема, увага зосереджена на можливостях інтеграції таких матеріалів у процеси просторової організації парків та рекреаційних зон, що є актуальним завданням сучасного містобудування. У дослідженні розглянуто ключові аспекти, що визначають експлуатаційний потенціал силікатних композитів, включаючи їх структурно-технологічні характеристики, показники довговічності, екологічної безпеки та естетичної привабливості.

Особливий акцент зроблено на аналізі потенційного використання силікатних композитів у створенні малих архітектурних форм, декоруванні відкритих просторів, а також у формуванні функціональних складових міського середовища. Представлені переваги цих матеріалів у контексті сучасного будівництва демонструють їх здатність забезпечувати не лише архітектурну виразність та функціональність об'єктів, але й знижувати фінансові витрати на їх будівництво, подальшу експлуатацію та обслуговування.

У статті зроблено акцент на важливості використання екологічно чистої сировини у виробництві силікатних композитів, що сприяє зменшенню негативного впливу на навколишнє середовище та відповідає принципам сталого розвитку в архітектурній практиці. Дослідження включає розрахунки та аналіз моделей, що демонструють зв'язок між структурними параметрами матеріалів та їх експлуатаційними характеристиками.

Зокрема, було проведено детальні дослідження таких фізико-технічних показників, як міцність на стиск, морозостійкість, водостійкість, щільність, тріщиностійкість та стійкість до карбонізації. Комплексний аналіз цих критеріїв дозволив зробити обґрунтовані висновки щодо перспектив використання силікатних композитів у проєктуванні архітектурних елементів навколишнього середовища, ландшафтному дизайні для об'єктів відкритого типу та раціональній організації зовнішніх просторів у сучасних міських умовах.

Ключові слова: силікатні композити, властивості, ландшафтний дизайн, відкрите середовище, екологія, експеримент.

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RESEARCH ON THE INFLUENCE OF MINERAL OILS ON THE STRENGTH AND AVERAGE DENSITY OF HEAVY CONCRETE

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Abstract. The article investigates the effect of mineral oils on the strength and volumetric weight of heavy concrete. Heavy concrete is the main material in construction, used to create structures with increased requirements for strength and stability, however, the effect of chemical agents, such as mineral oils, on its properties remains insufficiently studied. The study of this aspect is important for improving the durability and safety of concrete structures, in particular those exposed to oils in industrial processes or accidents. The aim of the study was to study how different types of mineral oils (transformer oil T-1500, engine oil 10W-40, IGP-30, both new and used) affect the physical and mechanical characteristics of heavy concrete, in particular its strength and volumetric weight. The experiments were carried out on concrete samples measuring 100×100×100 mm, made of Portland cement, under standard storage conditions. Oils were applied by two methods: immersion of samples in oil and application with a brush.

The results of the studies showed that the most significant effect on the strength and volumetric weight of concrete was the method of immersion of samples in new transformer oil T-1500, where after 30 days a significant increase in weight by 1.18% and compressive strength by 13.06% was observed. The use of waste oils and the method of applying oil with a brush led to a decrease in the strength of concrete, in particular, when using waste motor oil 10W-40, the strength decreased by 63.74% on day 30. At the same time, application of oil with a brush caused mainly superficial changes, without significant improvements or even a decrease in the strength of concrete. The results confirmed that the type of oil, its condition and the method of application have a significant effect on the mechanical properties of concrete. The study indicates the importance of choosing methods for protecting concrete structures from the negative effects of chemical agents and opens up prospects for further research in this area, in particular the development of technologies that reduce the impact of mineral oils on the durability and strength of concrete.

Keywords: heavy concrete, mineral oils, concrete strength, concrete average density, mechanical properties of concrete.

Introduction. Heavy concrete is one of the main materials used in construction, and it is widely used to create structures with increased requirements for strength and stability [1]. Despite its widespread use, questions remain about its durability and how its properties change under the influence of various external factors. One such factor is the influence of mineral oils, which are used in various industrial processes and can be present in the event of accidents or spills. Nevertheless, the mechanism by which mineral oils influence the physical and mechanical characteristics of concrete remains insufficiently studied.

Researching this issue is relevant because it provides a deeper understanding of how chemicals, particularly mineral oils, can alter concrete's basic properties, such as strength and density. These changes can significantly impact the performance of concrete structures, particularly their durability and safety. Since mineral oils have different chemical compositions and can be new or used, it is important to study how different types of oils affect concrete under various application methods. This research will contribute to a better understanding of the processes occurring in concrete under the influence of chemical agents and may form the basis for developing new recommendations for protecting concrete structures from aggressive influences. This is particularly relevant in industries where concrete is exposed to various chemicals.

Analysis of recent research sources and publications. The effect of mineral oils on the strength and average density of heavy concrete is an important topic in construction and materials science because using oils and petroleum products at various stages of construction can significantly impact concrete structure characteristics. Mineral oils, in particular, can alter concrete's physical and chemical properties, potentially decreasing its strength and durability.

Research into the effects of oils on concrete began several decades ago when serious defects caused by oiling concrete structures were discovered. Scientists such as K. Zelko, A. Bartosh, O. Volyansky, D. Plagin, T. Kostyuk, and V. Vinnichenko have devoted considerable attention to studying this phenomenon, focusing on the various ways oils impact the strength and durability of concrete structures. Notable foreign studies include the work of S. Stian, D. Weiss, R. Goshek, and W. Gray, which also confirm the importance of studying this issue.

One of the most notable studies is the research on how concrete strength decreases when it comes into contact with oil. One such study is by S. Chepurna, who found that oil – soaked concrete stops hardening and loses strength over time. Similar results were obtained in the study by Salau M. [14], who found a 12% decrease in the compressive strength of cement – sand mortar after two months of storage in lubricating oil.

Klymenko E. [4] found that storing concrete samples in mineral oil can lead to a 50% reduction in strength and that Portland cement concretes are more vulnerable to the effects of oils. Other researchers, such as Grynova, Shtukhets, Zelko, and Bartos, claim that oils decrease the axial tensile strength of concrete, particularly lower - grade concrete.

Studies on the effects of mineral oils on the physical and mechanical properties of concrete show that concrete with lower strength experiences a more pronounced decrease in strength. Diab H. [9] emphasizes that, after years of operation, oil – contaminated concrete can experience a 40-50% decrease in strength, with the greatest decrease observed in floor slabs. This is associated with the shape of the contact surface of structures.

Despite the significant number of studies indicating the negative impact of oils on concrete, some studies note that under conditions of short – term exposure to heavy oils, the reduction in strength may be insignificant. Rollo B. and Goshek Y. [13] note that the decrease in strength is only observed for three months. After this period, the strength stabilizes at a virtually constant level throughout the year. They also note that the extent of the decrease depends on the conditions of the concrete's initial hardening.

Additionally, there are scientific studies [10, 15] that suggest positive outcomes from various technological approaches to mitigating the impact of mineral oils on concrete. Research on protective coatings and special additives, for example, can help maintain concrete's resistance to the negative effects of petroleum products. This may include special repair methods and improvements to concrete mix composition.

Analysis of scientific publications shows that the influence of mineral oils on concrete strength is a multifaceted issue requiring further research, particularly regarding the development of methods to preserve the strength of structures in the event of prolonged contact with oils. Current research focuses on finding optimal materials and technological solutions that significantly increase the durability of concrete structures, even when they come into contact with petroleum products.

Setting goals and objectives. This study aims to investigate the impact of mineral oils on the physical and mechanical properties of heavy concrete, particularly its strength and average density. Additionally, the study seeks to identify the primary factors influencing these changes, including the type of oil, its condition (new or used), and the application method.

The research objectives include:

1. Assessing the effect of new and used mineral oils on concrete strength and density.

2. Comparing two methods of concrete interaction with oils (immersion and brush application) in terms of their effect on changes in concrete strength and density.

3. Analysis of changes in concrete's mechanical properties (compressive strength) after contact with different types of oils for varying lengths of time.

Materials and methods. The study aimed to investigate the effect of mineral oils on the mechanical properties of heavy concrete. The concrete cubes, which measured 100×100×100 mm, were made using Portland cement (PC II/A-B-500R-N, SEM II/A-LL 42.5 R), class C 32/40 (B40), river sand, crushed stone (5–20 mm), and water. The ratio of cement to sand to crushed stone to water was 1:2:4:0.5. The average cubic compressive strength of the control samples (without oil exposure) was 45.2 MPa after 28 days. Initial porosity (12.5%) was determined using the saturation and hydrostatic weighing method, in accordance with DSTU B V.2.7-170:2008. Water absorption (5.3%) was determined by the mass method in accordance with DSTU B V.2.7-170:2008. After exposure to mineral oils, the porosity of the samples decreased by an average of 1–2% when immersed and increased by 3–4% when applied with a brush. This is due to the oil partially filling or destroying the pores. Oil absorption was determined experimentally after contact. Samples were prepared and tested in accordance with DSTU B V.2.7-214:2009 "Concrete. Methods for Determining Strength Using Control Samples" and DSTU B V.2.7-170:2008, "Concrete. General Technical Conditions". The tests were carried out under standard conditions: a temperature of 20°C and a humidity level of 45%. Six types of mineral oils were selected for the study: T-1500 transformer oil (new and used), 10W-40 motor oil (new and used), and IGP-30 oil (new and used) (Table 1).

Table 1 – Mineral oils that interacted with concrete

Transformer T-1500 new	**Transformer T-1500 used**	**IGP-30 new**	**IGP - 30 spent**	**Engine oil 10W-40 new**	**Motor oil 10W-40 used**
					

In the study, the oils were used exclusively as external agents that interacted with the concrete. That is, the oils were not added to the concrete mixture, but rather, were applied to the surface of the samples by immersion or brush application. Therefore, the oils did not act as concrete additives or components, but rather simulated the conditions of concrete structures in contact with lubricants. The samples were kept in contact with the oils for 10 or 30 days. For the immersion method, the samples were fully submerged in oil in sealed containers. Brushing was performed daily. The thickness of the oil layer applied with a brush was approximately 0.5–1 mm, as determined by visual inspection and weighing the samples before and after application. The oils' effect was evaluated 10 and 30 days after contact with concrete. The physical and chemical characteristics of the oils used in the study are provided in Table 2. Waste mineral oils are lubricants that lose their original properties during operation, according to DSTU GOST 21046:2019 "Waste petroleum products. General technical conditions", DSTU 4058:2001 "Lubricating oils" and DSTU GOST 21046:2019 "Waste petroleum products. Terms and Definitions" and DSTU 2156-93 "Motor Oils. General technical conditions". These oils are characterized by the presence of oxidation products, metal impurities, and resinous compounds in their composition. The density (before and after the experiment), viscosity, and acid number were determined for each oil.

To assess the impact, measurements were taken to determine changes in average density and compressive strength. The average density of the samples was recorded before and after they came into contact with the oil using analytical scales. Strength was assessed using a standard compression test. Changes in properties were compared depending on the type of oil, whether it was new or used, and the application method. Each oil type was tested twice for each application method, and the results were analyzed using average values. Particular attention was paid to how the type of oil, method of application, and duration of exposure interacted to affect the mechanical properties of concrete.

Table 2 – Characteristics of mineral oils

Type of oil	Condition	Density before testing, g/cm³	Density after testing, g/cm³	Viscosity at 20°C, mm²/s	Acid number, mg KOH/g
Transformer T-1500	new	0.876	0.878	28	0.03
Transformer T- 1500	worked out	0.885	0.889	31	0.12
IGP-30	new	0.845	0.846	25	0.05
IGP-30	worked out	0.852	0.857	27	0.15
Engine oil 10W 40	new	0.874	0.875	90	0.04
Engine oil 10W-40	worked out	0.881	0.886	95	0.18

Research results. Concrete samples measuring 100×100×100 mm and made of Portland cement were used for the study. The samples were exposed to various types of mineral oils, including new and used T-1500 transformer oil, 10W-40 motor oil, and IGP-30 oil. The goal was to evaluate how oils affect the mechanical properties of heavy concrete, particularly its average density and compressive strength. To this end, two methods of oil application were employed: immersion of samples in oil and application of oil with a brush. The properties of the concrete were studied 10 and 30 days after contact with the oils.

The results demonstrated significant differences in concrete behavior depending on the type of oil, its condition (new or used), and the application method. According to the obtained data, the most significant effect on the change in concrete's average density and strength was observed when the samples were immersed in new T-1500 transformer oil. This oil exhibited the highest increase in bulk density and compressive strength after 10 and 30 days. Thus, 10 days after immersion, the average density of the samples increased by 1.14%; on the 30th day, it increased by 1.18%. This indicates the concrete structure actively absorbed the oil, likely contributing to a reduction in microcracks and an increase in the material's integrity. Conversely, applying oil with a brush did not cause significant changes in average density – only 0.05% after 10 days and 0.80% after 30 days – indicating superficial oil penetration.

The best results in terms of compressive strength were recorded when the samples were immersed in new T-1500 transformer oil. After 10 days, the samples' strength increased by 4.14%, and after 30 days, it increased by 13.06%. This is the highest increase among all types of oils. This indicates the positive effect of this oil on concrete's structural strength, particularly due to the oil partially filling the pores and reducing internal defects in the material. In contrast, using the brush application method decreased concrete strength: by 4.86% after 10 days and by 48.12% after 30 days. This indicates the oils' uneven and superficial effect on concrete.

Similar results were observed when using used T-1500 transformer oil. The change in average density of the samples after 10 and 30 days was similar to the results for new oil; however, the change in compressive strength was significantly lower. Specifically, the strength increased by 0.92% after 10 days and by 2.14% after 30 days. This indicates the limited effect of used oil containing oxidized products and contaminants, which can reduce the positive effect. Additionally, applying the oil with a brush caused a slight decrease in strength: 0.80% after 10 days and 6.57% after 30 days. This demonstrates the negative effect of used oil on concrete when using the surface application method.

A study of the effect of IGP-30 oil showed a lower ability to penetrate concrete compared to transformer oil. In particular, 10 days after immersion, the average density of the samples increased by 0.70%, and after 30 days – by 1.12%. Applying the oil with a brush led to a slight decrease in average density due to moisture evaporation from the concrete surface: 0.19% after 10 days and 40.35% after 30 days. At the same time, the strength of the samples increased by 2.71% on day 10 and by 12.19% after 30 days, confirming the positive effect of IGP-30 oil on concrete strength (Fig. 1), although less pronounced compared to T-1500 transformer oil.

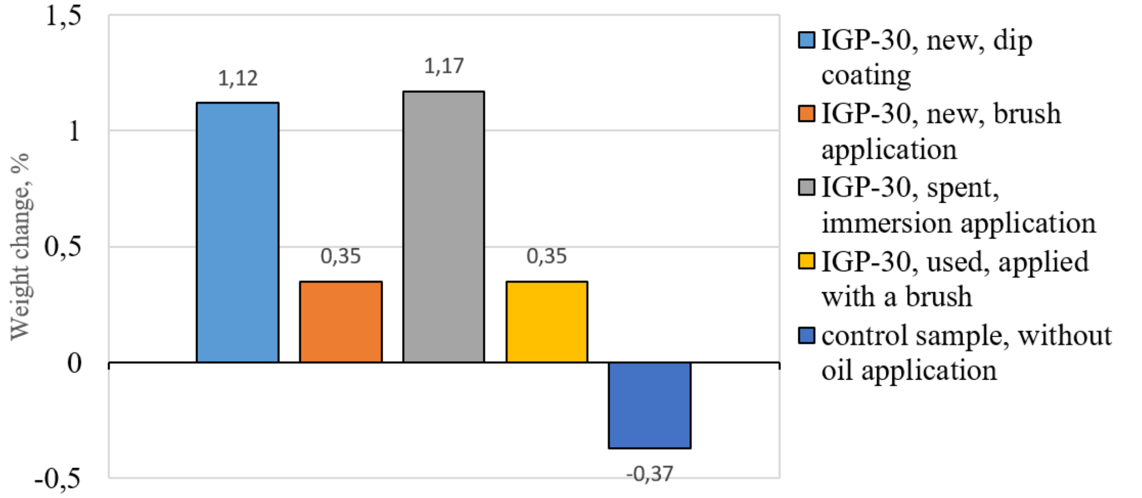

Fig. 1. Change in the average density of a concrete sample after interaction with IGP-30 oil (30 days relative to 1 day)

Opposite results were observed when using used IGP-30 oil. On the 10th day after immersion, the samples showed a decrease in strength by – 2.40%, and on the 30th day, this figure was – 4.88%. The greatest decrease in strength on the 30th day was recorded when applying the oil with a brush, which led to a decrease in strength by 84.11% (Fig. 2), which is the worst result among all the options studied.

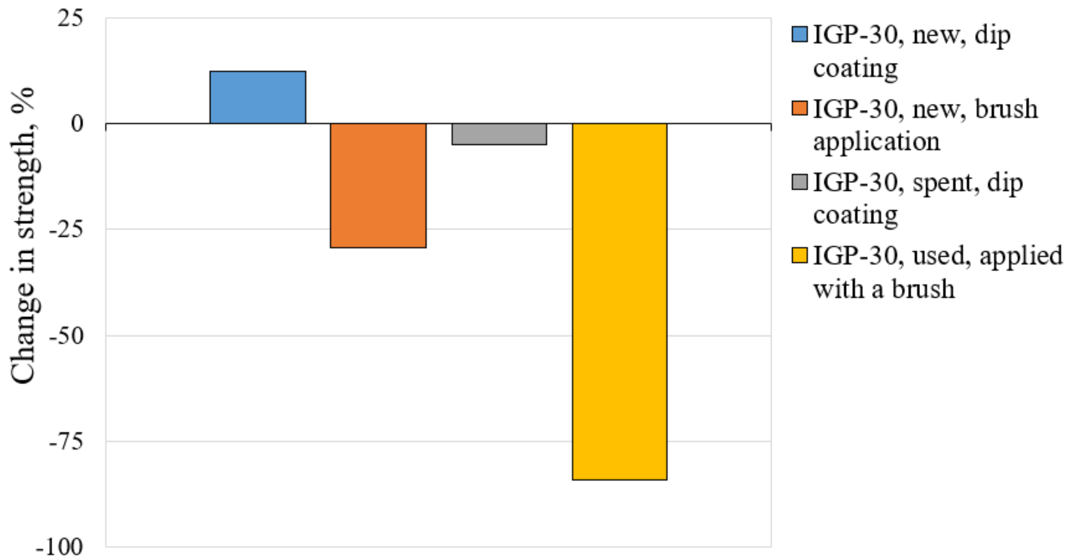

Fig. 2. Change in compressive strength of concrete sample after interaction with IGP-30 oil (30 days relative to 1 day)

As for 10W-40 motor oil, 10 days after immersion, the average density of the samples increased by 0.74%, which is an average indicator compared to other oils. At the same time, changes in compressive strength on day 10 showed a significant decrease of – 7.47%, which is the worst result among all new oils. The level of destruction is shown in the photo (Fig. 3).

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Fig. 3. Destruction on day 10 of a sample immersed in new 10W-40 motor oil

However, 30 days after immersion, the strength increased by 11.41%, indicating the possibility of compensating for the negative effect under conditions of prolonged contact with oil. At the same time, applying oil with a brush caused a significant decrease in strength by – 63.74% (Fig. 4), which is another confirmation of the negative effect of surface application of oils.

Fig. 4. Destruction of the sample after 30 days following the application of used motor oil 10W-40 with a brush

The worst result for used 10W-40 motor oil was observed after immersion, when after 30 days the strength decreased by – 11.04%. This confirms the negative impact of used oils on concrete during prolonged contact. The least impact was recorded when the oil was applied with a brush, where the strength decreased by only – 0.25% after 10 days and – 55.07% after 30 days.

Visual observations revealed the formation of a film and deposits on the concrete surface after contact with waste oils. The depth of oil penetration into the concrete structure was estimated from sample cuts and amounted to 5–7 mm when immersed and 1–2 mm when applied with a brush.

Overall, the results of the study confirm the importance of correctly applying oil to preserve concrete's strength. Immersing samples in oil produced significantly better results than applying oil with a brush. New oils, particularly transformer oil T-1500, had the most positive effect on concrete samples. Waste oils, especially IGP-30 and 10W-40 motor oil, had a significantly negative effect, particularly when applied with a brush. This indicates the importance of using high – quality materials and methods to preserve concrete strength when it is in prolonged contact with oils.

Analysis of the results also highlights the importance of further research on the effects of other types of oils and different exposure conditions for a more accurate understanding of the mechanisms of interaction between oil and concrete, which will allow the development of more effective strategies for improving the properties of concrete under various aggressive influences.

Research on the impact of mineral oils on concrete's mechanical properties has revealed that this effect hinges on the oil's type, condition (new or used), and application method. Immersing concrete samples in oil increases their average density, indicating that the oil penetrates the concrete's pores [6]. New oils, especially transformer oil, are more effective at increasing average density than used oils due to their homogeneous composition.

The effect on concrete strength was mixed: immersion in new oil increased strength, while used oils, in particular IGP-30 and motor oil, had a negative effect. This can be explained by chemical changes in used oils that contribute to concrete degradation. The brush application method often led to a decrease in strength due to uneven oil distribution.

To reduce the negative impact on concrete, it is recommended to use new oils and the immersion method for uniform saturation. To protect concrete structures, special coatings that reduce oil permeability should be developed [8]. Further research is needed to study the long – term effects and develop technologies that protect concrete from aggressive environments, such as mineral oils.

Conclusions. Research into the effect of mineral oils on the mechanical properties of heavy concrete has revealed key factors influencing changes in the structure of the material under the action of chemicals. The type of oil, its condition (new or used), and the method of application have a significant impact on concrete properties such as average density and compressive strength.

The new T-1500 transformer oil showed the best results, increasing the average density and strength of concrete, especially with the immersion method. After 30 days, strength increased by 13.06% and average density by 1.18%. Used transformer oil had a lesser effect due to the presence of oxidation products, which reduced the effectiveness of interaction with concrete. The new 10W-40 motor oil initially reduced the strength of concrete by 7.47%, but after 30 days, the positive effect increased to 11.41%. At the same time, used oil showed a significant decrease in strength when applied with a brush (a decrease of 55.07%). IGP-30 oil had a moderate positive effect when immersed (strength increased by 12.19%), while used oil applied with a brush caused a significant decrease in strength (- 84.11%), indicating the negative impact of oxidation products. The immersion method showed the best results, ensuring uniform saturation of the concrete, while brush application, especially with used oils, led to local damage to the concrete due to uneven oil distribution. Over time, after 30 days, the new oils contributed to improving the characteristics of the concrete, while the used oils caused a decrease in strength. The difference between new and used oils is due to their chemical composition: new oils have a more stable composition, while used oils contain resins and oxidation products that destroy concrete. The results obtained are consistent with the requirements of DSTU B V.2.6 - 156:2010, which stipulate increased density (not less than 2400 kg/m^3), low water absorption (up to 5%), and resistance to aggressive environments for concrete used in oil tanks. The samples that were in contact with the new T-1500 transformer oil met these indicators, confirming the suitability of heavy concrete for use in lubricant tanks, provided that the materials and oil application methods are correctly selected. Overall, the results of the study help to better understand the mechanisms of interaction between mineral oils and concrete and may be useful for improving construction technologies.

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ДОСЛІДЖЕННЯ ВПЛИВУ МІНЕРАЛЬНИХ ОЛИВ НА МІЦНІСТЬ І СЕРЕДНЮ ГУСТИНУ ВАЖКОГО БЕТОНУ

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Анотація. У статті досліджено вплив мінеральних олив на міцність і середню густину важкого бетону. Важкий бетон є основним матеріалом у будівництві, що використовується для створення конструкцій з підвищеними вимогами до міцності та стійкості, однак вплив хімічних агентів, таких як мінеральні оливи, на його властивості залишається недостатньо вивченим. Вивчення цього аспекту є важливим для покращення довговічності і безпеки бетонних конструкцій, зокрема тих, що піддаються впливу олив в умовах промислових процесів чи аварій.

Метою дослідження було вивчити, як різні типи мінеральних олив (трансформаторна олива Т-1500, моторна олива 10W-40, ІГП-30, як нові, так і відпрацьовані) впливають на фізико-механічні характеристики важкого бетону, зокрема його міцність і середню густину. Експерименти проводились на бетонних зразках розмірами 100×100×100 мм, виготовлених з портландцементу, за стандартних умов збереження. Оливи наносились двома методами: зануренням зразків у оливу та нанесенням пензликом.

Результати досліджень показали, що найістотніший вплив на міцність і середню густину бетону мав метод занурення зразків у нову трансформаторну оливу Т-1500, де через 30 днів спостерігалось значне збільшення середньої густини на 1.18% та міцності на стиск на 13.06%. Застосування відпрацьованих олив та метод нанесення оливи пензликом призводили до зниження міцності бетону, зокрема при використанні відпрацьованої моторної оливи 10W - 40 на 30 день міцність знизилась на 63.74%. Водночас нанесення оливи пензликом викликало переважно поверхневі зміни, без значних поліпшень або навіть зниження міцності бетону. Результати підтвердили, що тип оливи, її стан та метод нанесення мають суттєвий вплив на механічні властивості бетону. Дослідження вказує на важливість вибору методів захисту бетонних конструкцій від негативних впливів хімічних агентів і відкриває перспективи для подальших досліджень у цій галузі, зокрема розробки технологій, які знижують вплив мінеральних олив на довговічність та міцність бетону.

Ключові слова: важкий бетон, мінеральні оливи, міцність бетону, середня густина, механічні властивості бетону.

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DROPLET METHOD FOR INVESTIGATING THE CAPILLARY–POROUS STRUCTURE OF MATERIALS

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Abstract. A simple express methodology is proposed for the non-destructive characterization of the capillary–porous structure of building materials, based on monitoring the spreading dynamics of a colored droplet applied to the surface of a specimen. The method relies on recording the temporal evolution of the stain and interpreting the resulting $R^2(t)$ dependence within the Lucas–Washburn framework and porous-media theory. This enables, in a single experiment, the evaluation of effective porosity, capillary conductance, permeability, mean effective pore radius, effective diffusion coefficient, as well as wetting parameters (contact angle, surface tension) and indicators of deviation from the ideal capillary regime. The experimental procedure consists of video recording the spreading of a droplet of aqueous dye solution (e.g., methylene-blue), followed by frame extraction and computer processing of the stain contours. From the stain area, an equivalent radius is obtained, the $R^2(t)$ relationship is constructed, and its slope is used to extract integral capillary characteristics of the material. The approach provides high informational value at minimal equipment cost, making it suitable for field applications and preliminary screening of restoration zones. Using shell limestone as an example, it is demonstrated that the method allows quantitative identification of structural variations even within a single block or layer-an essential requirement for selecting compatible primers and restoration mortars with controlled rheological and adhesive properties. A consistent data-processing workflow is outlined: linearization of the $R^2(t)$ dependence, determination of capillary conductance, evaluation of effective porosity from the absorbed liquid volume, and reconstruction of permeability and contact angle values based on known liquid parameters. Verification criteria for assessing the plausibility of the obtained values are presented, including penetration depth and typical ranges of permeability and mean pore radii for cemented carbonate rocks. The proposed methodology effectively complements diagnostic approaches already used in restoration practice and provides a parametric basis for selecting mixtures adapted to the real geometry of the substrate's capillary–porous network. Thus, the developed droplet-based analysis toolkit combines operational simplicity with the ability to obtain key structural characteristics required for scientifically grounded design of repair and restoration solutions for shell limestone e heritage objects.

Keywords: capillary–porous structure, droplet spreading, Lucas–Washburn method, shell limestone, restoration materials.

Introduction. Assessing the capillary–porous structure of calcite-containing rocks, particularly shell limestone, is essential for the justified selection of restoration and plaster compositions. Adhesion, deformation and filtration compatibility, water absorption, vapor permeability, and the overall durability of the "substrate–coating" system are directly governed by the geometry and connectivity of the pore space. For shell limestone, this is especially critical due to the high structural heterogeneity even within one layer and the sensitivity of the surface to local variations in microrelief, which makes it difficult to ensure reliable contact of the restoration material with the base and requires taking into account the individual characteristics of the restoration areas. That is why modern approaches insist on a preliminary physico-chemical analysis of the surface and adjustment of the composition according to operational properties in compliance with the requirements of authenticity and compatibility, which for shell limestone objects acquires the status of a mandatory technological stage.

The express method proposed in the work is based on the registration of the time evolution of a stained liquid spot that spreads along a capillary–porous network near the surface of the sample. The method is attractive because it combines experimental simplicity with high informational value: video recording of the process and elementary computer processing of the contours are enough to obtain a set of integral parameters of the porous medium from the $R^2(t)$ curve. In practice, a methylene-blue solution was used. The video was split into frames, the spot area and geometric parameters were measured, circularity was evaluated, and the relevant physical quantities were computed – all without damaging the sample, with minimal equipment requirements, and with the possibility of performing the procedure directly on the object. Such a ratio of "simplicity of measurement – significance of results" is especially attractive for monument conservation work, where full-scale laboratory methods are often impractical or impossible at all.

Here it is appropriate to briefly review the theoretical principles of the method. Under the condition of dominance of capillary forces, the spread of a drop in the approximation of an isotropic pore network obeys the Lucas–Washburn law, which leads to a linear of $R^2(t)$ on time. It should be noted that real samples of shell limestone are rarely isotropic. The presence of internal boundaries of division, microcracks and zones of inhomogeneous cementation locally changes the paths of liquid filtration, leading to deviations from the ideal Lucas–Washburn capillary regime. Such effects are manifested in the form of a change in the slope of the $R^2(t)$ dependence at certain time intervals or in the appearance of weak anisotropy of the spot. However, for small drop volumes and dominance of wetting over gravity, these deviations do not violate the overall linearity, and therefore can be taken into account as part of the effective parameters φ_{eff} and K_c. The slope of this dependence is interpreted as the capillary conductance coefficient K_c (hereinafter denoted A), which in combination with known fluid parameters (dynamic viscosity μ and surface tension γ) and hydrophilic-hydrophobic surface properties (contact angle θ) allows us to reconstruct the structural characteristics of the material. When the absorbed volume $V(t)$ or sample thickness is known, the method yields the effective porosity φ_{eff}. From the capillary pressure or front velocity, the effective pore radius reff can be estimated. With reference values of γ, μ and θ, the intrinsic permeability k can also be derived. The set of these quantities forms a "passport" of the porous medium, in which A, φ_{eff}, k, r_{eff}, θ, D_{eff}, are mutually consistent and allow us to control the plausibility of the estimates for the spot geometry, penetration depth, and ranges typical of cemented carbonate rocks.

The practical relevance of the measured characteristics for the selection of restoration and plaster compositions lies in the direct connection between the parameters of the pore network of the base and the formulation solutions. Knowing φ_{eff} and k, the permissible intervals of water consumption, wetting and drying rates are established and the structure of the binder matrix (lime/cement ratio, proportion of microfillers) is selected to ensure compatibility in terms of filtration capacity and avoid excessive capillary suction, which provokes salt migration. The parameter r_{eff} focuses on the granulometry of the aggregate and microfillers: the particle distribution should "hook" the dominant pore channels for reliable mechanical fixation without clogging the vapor paths. The wetting angle θ and the associated wetting energy control the choice of hydrophilic-hydrophobic modifiers and primers, which allows balancing adhesion and capillary water absorption and reducing the risk of formation of efflorescence defects. The D_{eff} estimate helps predict the kinetics of moisture and dissolved salt transport in the base–layer system, setting maintenance regimes and operational constraints. In conclusion, the described approach provides a parametric basis for adapting the composition to a specific shell limestone surface, which is consistent with modern practice in material selection for historical sites and complements other methods of surface structural analysis.

Unlike more complex methods that require specialized microscopy and separate laboratory measurements of hydrophobicity and texture parameters, the express drop approach allows you to quickly obtain a consistent set of target values directly on the site, and the obtained parameter intervals for limestone and shell limestone serve as additional verification of the realistic estimates and the basis for making design decisions. Such a balance of simplicity of the procedure and the significance of the results corresponds to the task of scientifically based selection of restoration and plaster systems for objects made of shell limestone.

Analysis of literature sources. Capillary wetting and imbibition in porous building materials – from classical equations to express methods based on the "dye drop" – remain one of the most informative approaches for non-destructive diagnostics and selection of restoration and plaster compositions. In modern works, the general dynamics of the front is described by the Lucas–Washburn law, which leads to a linear dependence of $R^2(t)$ on time under the dominance of capillary forces. Deviations from Lucas–Washburn are associated with inertial effects, gravity, wettability, angle hysteresis and multimode pore distribution [1–5]. For thick porous substrates, analytical solutions are consistent with observations of a drop that simultaneously spreads and infiltrates, and corrections to Lucas-Washburn scaling are proposed [3]. In parallel, two-phase models based on filtration/porous media equations (Richards/LBM/PNM) generalize Lucas–Washburn to cases of partial saturation and complex pore geometry [2, 4, 6]. Against this background, "field" protocols (RILEM II.4, ASTM C1585) provide standardized capillary indices (capillary absorption coefficient, drying index) and are widely used in stone conservation to assess the effectiveness of water repellents and salt resistance [7–12].

The express approach with fixation of the spread of a colored drop directly implements the Lucas–Washburn framework: from the slope $R^2(t)$ the combined coefficient of capillary conductance K_c is extracted, and with a known volume of absorbed liquid $V(t)$ the effective porosity φ_{eff} is obtained; with additional data – to the permeability k, the effective pore radius r_{eff} (due to capillary pressure or the Kozeny–Carman correlation) and, sometimes, to θ [1–4]. The linearity of $R^2(t) \sim t$ is a diagnostic feature of the capillary regime and allows us to estimate K_c, φ_{eff} and r_{eff} for shell limestone. In practice, this is implemented through frame-by-frame analysis of the spreading methylene-blue drop, followed by measurement of the spot geometry, linear regression of the $R^2(t)$ on time, and subsequent substitution into the basic Lucas–Washburn and Kozeny–Carman relations.

Compared to laboratory methods (mercury porometry, N_2/BET adsorption, MRI/NMR relaxation, microCT), the "drop method" has the advantages of simplicity, low cost and sensitivity to surface changes, which is critical for assessing the compatibility of restoration systems with a porous base. However, classical standards also take into account limitations: locality of measurement, the influence of texture/anisotropy and surface preparation mode. Therefore, in conservation practice, it is advisable to combine it with RILEM/ASTM standards, which calibrate the absorption rate on representative scales and allow validating trends "before"/"after" treatments [7-12]. At the foundation level, generalized analyses show that Lucas–Washburn scaling works well in mesoporous/macroporous carbonates before the appearance of capillary competition and gravitational effects. Network and micromodel experiments quantify the validity and deviation domains [5, 6].

For carbonates of the shell limestone type, recent petrophysical studies highlight the wide variability of pore types/sizes and connectivity, which directly determines k, φ_{eff}, electrical conductivity and degradation behavior. Pore-permo correlations for shell limestone differ from those typical for microporous limestones and require local calibrations [2, 13]. For restoration practice, this means the need to select soil-plaster-finish systems that match the capillary conductance and the "breathability" of the substrate: too low K_c/φ of the composition relative to the substrate will contribute to the accumulation of salts/moisture at the interface and delamination; a consistent capillary profile reduces the risks of salt weathering [8, 10]. That is why it is advisable to use fast "drop" indices (slope $R^2(t)$, estimate K_c, φ_{eff}) as screening criteria when selecting compositions for more laborious test cycles (RILEM II.4, accelerated salt weathering) [7, 8, 10].

An important modern line is the convergence of "droplet hydrodynamics" with digital morphometry and fractal surface descriptors: fractal dimension (by box-counting, triangular prisms, power spectrum, variational method) correlates with roughness/texture and affects the effective wetting angle, initial spreading and local infiltration [14–17].

In applied works for shell limestone, it has been shown that fractal metrics provide a quantitative basis for assessing "geometric smoothing" after priming: the difference in fractal dimensions before/after treatment can serve as a criterion for selecting a composition taking into account adhesive-capillary compatibility [16].

The combination of express droplet kinetics with fractal analysis of surface images forms a complementary set of indicators for the prompt but well-founded selection of restoration and plaster systems for a specific shell limestone.

In general, the comparison of approaches shows the following: Lucas–Washburn/droplet techniques are the most accessible for capillary mass transfer screening and preliminary selection of compositions; RILEM/ASTM standards are necessary for validated quantitative assessment and comparison of "before/after" treatments. Fractal morphometry is a bridge between surface geometry and wetting hydrodynamics, which allows setting target parameters of "compatibility" of restorative materials with a specific porous substrate.

The purpose of the work is to develop and test an express method for determining the capillary–porous characteristics of shell limestone based on the dynamics of droplet spread, taking into account the influence of internal separation boundaries and microcracks, determine the conditions for the applicability of the Lucas–Washburn approximation, and obtain generalized (effective) parameters φ_{eff}, k, r_{eff}, suitable for scientifically substantiated selection of restoration and plaster compositions.

Materials and research methods. In the study, shell limestone was used as a model material, which is characterized by a pronounced capillary–porous structure and high heterogeneity of pore size distribution. Samples were taken from typical blocks used in the masonry of historical buildings, while the surfaces for research were previously cleaned of dirt and dust without additional grinding in order to preserve the natural relief. An aqueous solution of dye (methylene blue) was used as the working fluid, which provided a distinct contrast of the stain against the stone background and did not significantly change the physicochemical parameters of water (viscosity, surface tension).

The measurement method consisted of applying a drop of known volume (0.02–0.05 ml) to the sample surface using a micropipette. Further spreading and absorption of the liquid were recorded using a digital video camera in real time. The resulting video files were divided into frames, after which the contours of the spot were determined using software analysis. The equivalent radius $R(t)$ was calculated from the spot area, the dynamics of which were monitored throughout the experiment.

Research results. From the analysis of the dependence of the spot radius on time, several key properties of the capillary–porous structure can be identified. Below is a model proposal, according to the method of which each property is determined.

Based on the dependence of the radius $R(t)$ on time, it is possible to determine the effective porosity φ_{eff}, the capillary conductivity coefficient K_c, the average effective pore radius r_{eff}, the coefficient of diffusion of liquid in a porous medium D_{eff}, (wetting angle θ, surface tension γ, if not previously known, permeability of the material k, volumetric resistance to liquid movement, and the deviation index from the ideal capillary regime (if observed).

Some of the above parameters were determined in the course of studying shell limestone, which is the primary material forming and undergoing restoration in historic buildings. These values are very important for making informed choices about plaster and restoration compounds.

The dependence of the radius of a water or other solvent or colored solution spot on time is determined by the Lucas–Washburn model. If capillary forces dominate, then according to the Lucas–Washburn equation (1):

$$R^2(t) = \frac{\gamma \cos\theta}{2\mu} \cdot \frac{k}{\varphi_{\text{eff}}} \cdot t \,, \tag{1}$$

where $R(t)$ is the radius of the spot, γ is the surface tension, θ is the wetting angle, μ is the viscosity of the liquid, k is the permeability, φ_{eff} is the effective porosity.

From experimental data, the model allows determining the combined capillary conductivity coefficient (2):

$$K_c = \frac{\gamma \cos\theta}{2\mu} \cdot \frac{k}{\varphi_{\text{eff}}} \,. \tag{2}$$

It is extracted from linear regression using the experimental dependence $R^2 \sim t$. If the amount of absorbed liquid $V(t)$ is known, the method allows to proceed to the effective porosity (3):

$$\varphi_{\text{eff}} = \frac{V(t)}{\pi R^2(t)h}, \qquad (3)$$

where h is the thickness of the material.

To determine the average pore radius, capillary pressure is used (4):

$$\Delta P = \frac{2\gamma \cos\theta}{r_{\text{eff}}}. \qquad (4)$$

If pressure information is available, r_{eff} can be determined. The effective radius value can also be obtained by expressing it in terms of the front velocity using an adapted Lucas–Washburn model.

For capillary diffusion, an analogy with diffusion is sometimes used. The effective diffusion coefficient D_{eff} includes the parameters of capillary transport. Analysis of the $R^2(t)$ graph allows us to estimate D_{eff} (5):

$$R^2(t) \sim D_{\text{eff}} t. \qquad (5)$$

If γ, μ, k and φ_{eff} are known, $\cos\theta$ can be expressed from the expression for K_c, and then the angle itself. This is relevant for porous materials when the contact angle can be directly determined by the absorption of liquid by the porous material.

The experimental dependencies obtained reflect the combined effect of microstructural factors – porosity, cracking and internal border section between grains. Within the proposed approximation, they are integrated into the concepts of "effective porosity" and "effective permeability". Thus, even in the presence of small cracks or porous areas of varying connectivity, the results are interpreted as averaged characteristics of the macroporous network. This ensures the accuracy of the method for evaluating real restoration materials and natural stones with complex structures.

Practical part. The practical implementation of the used methods was based on the processing of the drop image obtained by frame-by-frame video recording of the spread of a drop stained with methylene blue solution. Some frames of this video storyboard are given in Fig. 1.

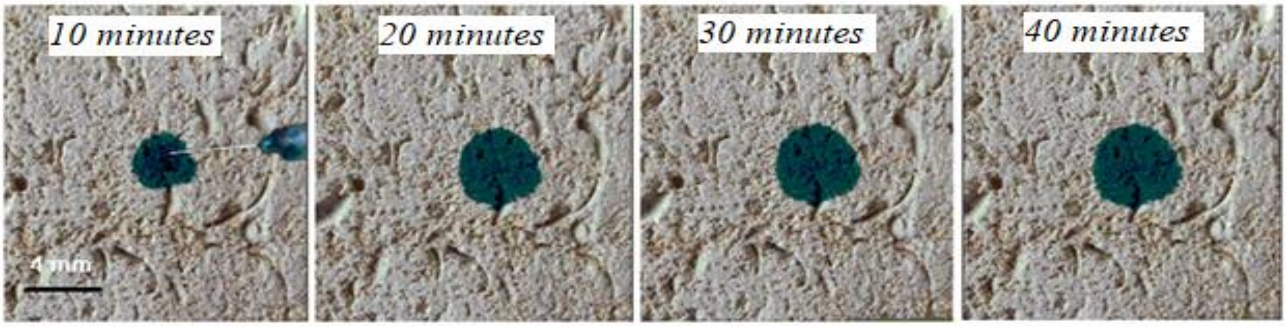

Fig. 1. The process of spreading a stain of a diluted solution of methylene blue on a sample of shell limestone

By analyzing these and other images using the Scion Image package, data on the shape and size of the spot were obtained, which are presented in Table 1.

Table 1 – Geometric characteristics of the size and shape of a liquid spot

No.	*Area*	*Perim*	*Major axes*	*Minor axes*	*Angle*	*Circle*	*AR*	*Round*
1	5.430	9.979	2.828	2.445	119.093	0.685	1.157	0.865
2	10.350	13.043	3.691	3.570	138.976	0.765	1.034	0.967
7	12.770	14.387	4.193	3.877	112.399	0.775	1.082	0.925
3	18.360	17.398	5.069	4.612	97.030	0.762	1.099	0.910
4	19.400	16.793	5.131	4.814	95.375	0.865	1.066	0.938
5	19.420	17.695	5.170	4.783	102.179	0.779	1.081	0.925
6	20.770	17.404	5.209	5.077	98.306	0.862	1.026	0.975

In Table 1 the following notations are used:

– *Area* – spot area, square millimeters;

– *Perim* – perimeter (length of the outer border of the spot);

– *Major axes* – major axis of the approximating ellipse (by length);

– *Minor axes* – minor axis of the approximating ellipse (in width);

– *Angle* – the angle between the main axis and the line parallel to the abscissa axis in the image;

– *Circ* – a measure of roundness. A value of 1.0 indicates that the circle will be perfect. The closer this value is to 0.0, the more elongated the resulting circle will be (6):

$$Circ = 4\pi \frac{(Area)}{(Perim)^2}, \tag{6}$$

– *AR* – measure of roundness. Ratio of axes of approximating ellipse (7):

$$AR = \frac{Major\ axes}{Minor\ axes}, \tag{7}$$

– *Round* – a measure of roundness, which is calculated by the formula (8):

$$Round = 4 \frac{(Area)}{\pi(Major\ axes)^2}. \tag{8}$$

A value of 1.0 indicates perfect roundness of the spot.

The values of the roundness measures in Table 1 indicate the adequacy of the assumption of roundness of the drop in the calculations. Therefore, to obtain the initial data (the square of the radius), the spot plane can be used, which was done.

The practical implementation of the considered methodology is carried out in the following sequence:

1. Plotting the graph of the dependence of R^2 on time. If the dependence is linear, then the system is controlled by capillary transport.

2. Determination of the slope coefficient $A = \frac{dR^2}{dt}$.

3. Calculate $K_c = A$.

4. Calculate φ_{eff} based on the volume of absorbed liquid.

5. Taking into account data on the physical properties of the liquid, the missing parameters φ_{eff}, θ, k, etc. are calculated from the model.

Graph of the dependence of R^2 on time (Fig. 2)

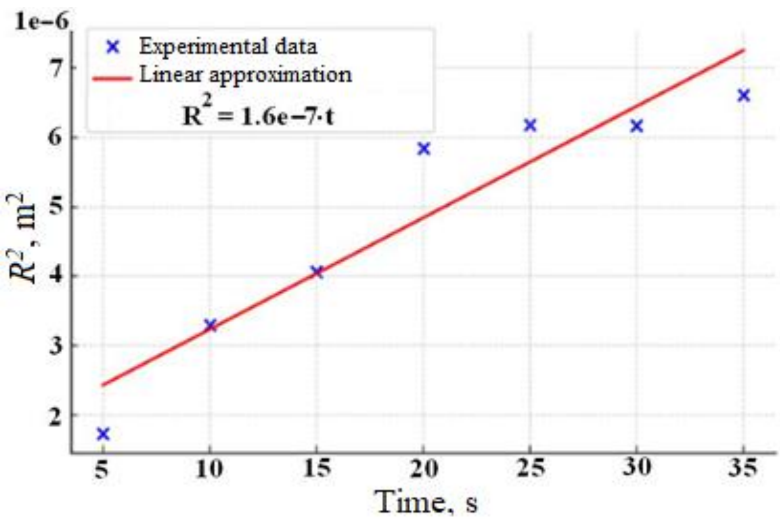

Fig. 2. Dependence of R^2 on time, and its linear approximation

The dependence of R^2 on time and its linear approximation shows that the spread of a spot in a porous material obeys the linear Lucas–Washburn law (9):

$$R^2(t) = A \cdot t\,, \tag{9}$$

where $A = 1.61 \cdot 10^{-7}$ m²/s.

The Lucas–Washburn equation allows us to proceed to the calculation of structural characteristics. The basic formula for calculating structural properties (10):

$$A = \frac{\gamma \cos\theta}{2\mu} \cdot \frac{k}{\varphi_{\text{eff}}}. \tag{10}$$

Let us calculate it relatively according to the following relation (11):

$$\frac{k}{\varphi_{\text{eff}}} = \frac{2\mu A}{\gamma \cos\theta}, \tag{11}$$

where $A = 1.61 \cdot 10^{-7}$ m²/s is found from the graph, $\mu = 1.0 \cdot 10^{-3}$ is the viscosity of water, $\gamma = 0.072$ N/m is the surface tension of water. The average wetting angle, according to the previous experiment, was $\bar{\theta} \sim 36°$, then $\cos(\bar{\theta}) \sim 0.8$. Substituting the values, we obtain (12):

$$\frac{k}{\varphi_{\text{eff}}} = \frac{2 \cdot 1.0 \cdot 10^{-3} \cdot 1.61 \cdot 10^{-7}}{0.072 \cdot 0.8} \approx 5.59 \cdot 10^{-9}\, m^2. \tag{12}$$

This relation $k / \phi_{\text{eff}} \approx 5.59 \cdot 10^{-9}\, m^2$ combines the permeability of the material k, m², and the effective porosity ϕ_{eff} (dimensionless volume fraction). If we assume $\phi_{\text{eff}} = 0.25$ (realistic for shell limestone), then (13):

$$k \approx \phi_{\text{eff}} \cdot \frac{k}{\phi_{\text{eff}}} = 0.25 \cdot 5.59 \cdot 10^{-9} = 1.40 \cdot 10^{-9}\, m^2. \tag{13}$$

For limestones and shell limestone, typical permeability values are shown in Table 2.

Table 2 – Typical permeability values for different materials

Material	Permeability k, m²
Fine sand	10^{-11} - 10^{-12}
Limestone	10^{-14} - 10^{-11}
Shell limestone	10^{-10} - 10^{-8}

The result obtained $k \approx 1.29 \cdot 10^{-9}\, m^2$. This is consistent with the range of porosity values of shell limestone, especially those that have been exposed to weathering or have natural cracks.

Let's check by the volume of the liquid. The volume of the solution $V = 0.02$ ml $= 2 \cdot 10^{-8}\, m^3$ Maximum spread area (according to the last value): $S_{\max} = 20.77\ cm^2 = 2.077 \cdot 10^{-5}\, m^2$. Let's estimate the average penetration depth: $h = \frac{V}{S} = \frac{2 \cdot 10^{-8}}{2.077 \cdot 10^{-5}} \approx 0.96\ mm$. Penetration depth < 1 mm – plausible for tests with an aqueous solution on dense but porous limestone or shell limestone.

The assessment of the plausibility of the results for the shell limestone is summarized in Table 3.

Table 3 – Plausibility assessment of results for the shell limestone

Parameter	Value
Coefficient A	$1.61 \cdot 10^{-7}$ m²/s
$\frac{k}{\phi_{\text{eff}}}$	$5.59 \cdot 10^{-9}$ m²
Estimate k at $\phi_{\text{eff}} = 0.25$	$1.40 \cdot 10^{-9}$ m²
Penetration depth assessment	~ 0.96 mm
Plausibility	High for a shell limestone

Estimate the average pore radius r_{eff} using the approximate formula – a consequence of the Kozeny–Carman equation (14):

$$k = \frac{r_{\text{eff}}^2}{8} \cdot \frac{\varphi_{\text{eff}}}{\tau} \quad \Rightarrow \quad r_{\text{eff}} = \sqrt{\frac{8k\tau}{\varphi_{\text{eff}}}} . \qquad (14)$$

For different values of tortuosity typical for a shell limestone τ (Table 4):

Table 4 – Estimated average pore radius at different tortuosity values

Tortuosity τ	r_{eff}, mm
1.5	0.249
2.0	0.287
2.5	0.321

Thus, a pore radius of ~0.25–0.32 mm is a plausible estimate for cemented carbonate rocks such as shell limestone.

Estimate the pore density (number of pores per 1 m^2). For this we will use the relation (15):

$$N = \frac{\varphi_{\text{eff}}}{\pi r_{\text{eff}}^2} . \qquad (15)$$

The results of calculations for three characteristic values of the pore radius are given in Table 5.

Table 5 – Pore density at different average radius values

Pore radius r_{eff}, mm	The number of pores per 1 m^2, pcs
0.249	1 284 900
0.287	963 700
0.321	770 940

The number of pores of about 1 million per square meter is quite typical for porous limestone and shell limestone. Let us make a general assessment of the plausibility of the obtained results (Table 6).

Table 6 – Assessment of the plausibility of the obtained values

Characteristic	Value	Plausibility for a shell limestone
Permeability k	$1.40 \cdot 10^{-9}$	High – within typical values
Pore radius r_{eff}	0.25 – 0.32 mm	Characteristic range
Penetration depth	~0.96 mm	Expected when saturated
Pore density	$0.7 – 1.3 \cdot 10^6$ pores/m^2	Realistic

Conclusions. Comparison of the results with data from literature sources indicates their adequacy to the typical characteristics of the materials under study. Given the influence of internal boundaries and microcracks, the method should be considered an effective approximation that is valid in cases where capillary forces prevail over gravitational forces and the filtration process is not accompanied by the opening or change in the geometry of cracks. Under such conditions, the parameters φ_{eff}, k, r_{eff} reflect the integral response of the porous medium and remain suitable for quantitative identification of the structure. However, since each sample of shell limestone has a unique pore structure, which is associated with different conditions of its origin and different nature of environmental influences, the study of the capillary–porous structure should be carried out for each restoration object separately. Thus, the goal of the work – verification of the suitability and limits of applicability of the drop method for real heterogeneous carbonate rocks – has been achieved. The results confirm the possibility of using effective parameters φ_{eff}, k, r_{eff} for parametric selection of restoration compositions. The simplicity and ease of implementation of the proposed method allow for easy application of the method directly in the conditions of restoration of a cultural heritage object.

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КРАПЕЛЬНИЙ МЕТОД ДОСЛІДЖЕННЯ КАПІЛЯРНО-ПОРИСТОЇ СТРУКТУРИ МАТЕРІАЛУ

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Анотація. Запропоновано просту експрес-методику неруйнівного аналізу капілярно-пористої структури будівельних матеріалів за динамікою розпливу краплі забарвленої рідини поблизу поверхні зразка. Метод ґрунтується на реєстрації часової еволюції плями та подальшій інтерпретації залежності $R^2(t)$ у рамках рівняння Лукаса–Вашбурна й підходів теорії пористих середовищ, що дає змогу з єдиного експерименту оцінити ефективну пористість, коефіцієнт капілярної провідності, проникність, середній ефективний радіус пор, ефективний коефіцієнт дифузії, а також параметри змочування (кут змочування, поверхневий натяг) і показники відхилення від ідеального капілярного режиму. Експериментальна реалізація базується на відеореєстрації розтікання краплі водного розчину барвника (зокрема метиленового синього) з подальшим кадруванням та комп'ютерною обробкою контурів плями; з площі плями визначається еквівалентний радіус, будується залежність $R^2(t)$, за нахилом якої одержують інтегральні капілярні характеристики матеріалу. Такий підхід забезпечує високу інформативність за мінімальних вимог до обладнання, придатний для польових випробувань і первинного сортування ділянок реставраційних робіт. На прикладі вапняку-черепашнику показано, що метод дозволяє кількісно ідентифікувати варіації структури навіть у межах одного шару або блока, що критично важливо для підбору сумісних ґрунтовок і реставраційних розчинів із заданими реологічними та адгезійними властивостями. Запропоновано послідовність оброблення даних: лінеаризація $R^2 - t$, оцінка капілярної провідності, перехід до ефективної пористості за об'ємом поглиненої рідини, відновлення проникності та кутів змочування з урахуванням відомих фізичних параметрів рідини; наведено критерії перевірки правдоподібності розрахунків (глибина проникнення, характерні діапазони проникності та середніх радіусів пор для цементованих карбонатних порід). Методика органічно доповнює прийняті в реставраційній практиці підходи попередньої діагностики поверхні та слугує основою для параметричного добору складів, адаптованих до реальної геометрії капілярно-пористої мережі субстрату. Таким чином, розвинений інструментарій аналізу розпливу краплі поєднує простоту виконання з можливістю отримання ключових структурних характеристик, необхідних для науково обґрунтованого проектування ремонтно-реставраційних рішень для об'єктів із вапняку-черепашнику.

Ключові слова: капілярно-пориста структура, розтікання краплі, метод Лукаса–Вашбурна, вапняк-черепашник, реставраційні матеріали.

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THE EFFECT OF MECHANICAL ACTIVATION OF MIXED PORTLAND CEMENT IN THE PRESENCE OF A SUPERPLASTICIZER ON THE COMPRESSIVE STRENGTH OF CEMENT STONE

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Abstract. The presented article provides experimental results related to determining the influence of mechanic activation of mixed Portland cement and a superplasticizing admixture on the physical and mechanical properties of cement stone under compression at the ages of 3, 7, and 28 days. Such cement was obtained by mixing Portland cement PC-I 500 with ground quartz sand, the amount of which varied within the range of 30–60 % of the total binder mass. A promising method for increasing the compressive strength of cement stone is intensive mechanic and chemical activation of mixed cement in a high-speed turbulent-type activator in the presence of a superplasticizer SP-5, the content of which varied from 0 to 1 % of the binder mass.

The research was carried out using D-optimal mathematical experimental design, with variation of the following factors: consumption of ground quartz sand (45 ± 15) % of the mixed binder mass and the amount of superplasticizing admixture (% of the mixed binder mass). The cement-water mixture was prepared using two technologies: the first with a high-speed activator (rotor speed 1500 rpm) and the second by traditional (control) mixing. The obtained mathematical models indicate a significant influence on the compressive strength of the cement stone by both the formulation factors (X_1, X_2) and the technological parameters of the mixing process. It should be noted that the combined effect of mechanic and chemical activation, the amount of ground sand, and the superplasticizer makes it possible to increase the compressive strength of the cement stone (compared to the control) by 22…41 %, which allows a substantial increase in the proportion of ground quartz sand in the mixed binder composition as a mineral additive to cement.

Keywords: mechanic activation, Portland cement, superplasticizer, mineral additive, compressive strength, variable factors.

Introduction. It is known that one of the key problems in the technology of production of mixed cements is the formation of optimal combinations of Portland cement with mineral additives, which allows to increase the potential properties of the binder. Quartz sands have become widespread as a mineral additive to cements, the presence of which in their composition ensures not only a reduction in the cost of the mixed binder, but also provides a number of positive properties to the cement stone (reduction of shrinkage, reduction of the magnitude of exothermic heating, etc.). The article considers the influence of mechanical and chemical activation of Portland cement, the amount of ground quartz sand and superplasticizer on the compressive strength of the cement stone. In our opinion, the combined use of ground quartz sand, superplasticizer, mechanical and chemical activation of the mixed binder contributes to obtaining cement stone with increased compressive strength.

Analysis of recent research and publications. One of the most common ways to reduce the cost of Portland cement is to introduce finely ground inert mineral additives, in particular, ground sand [1-5]. Technologically, such cement can be obtained both by joint grinding of Portland cement clinker, dihydrate gypsum and mineral additive, and by thorough mixing of Portland cement with ground mineral additive [6-9].

In works [10-15] it is convincingly shown that the effect of adding mineral additives to Portland cement is significantly enhanced in conditions of turbulent flows, which are achieved in the process of mechanical and chemical activation of mixed cement. In our opinion, the use of high-speed mixers for cement activation in combination with ground quartz sand and a superplasticizer will accelerate the cement hydration processes, which will allow to abandon both thermal and wet processing and the use of scarce rapid-setting cements.

Purpose and objectives. The above has determined the purpose of the study, which is to study the effect of mechanochemical activation of Portland cement with the addition of ground quartz sand (30–60 %) and superplasticizer SP-5 (0...1 %) on the compressive strength of cement stone after 3, 7 and 28 days.

Portland cement activation was carried out by intensively influencing the water-cement and cement-sand mixture (S_{sand} = 350 m^2/kg) in a high-speed turbulent mixer for 2 minutes. The use of a high-speed mixer contributes to the physicochemical activation of the surface layer of both fine grains of Portland cement and grains of ground quartz sand. The presence of activation ensures the intensification of cement hydration processes, which is reflected in the increase in the strength of the cement stone, especially in the early stages of hardening. The turbulent mixer is characterized by a high speed of rotation of the working body, which is 1500 rpm.

Materials and research methods. Experimental studies were conducted using Portland cement brand PC-I 500 of PJSC "Volyn Cement" as a binder. According to its properties, Portland cement meets the requirements of DSTU B.V.2.7-46:201 "Cements for general construction purposes. Technical conditions". Cement-sand binder was obtained by thoroughly mixing Portland cement and ground quartz sand, the consumption of which ranged from 30 to 60 % of the mass of the mixed binder. The specific surface area of ground quartz sand was taken to be 350m^2/kg. Plasticization of the mixture was carried out using superplasticizer SP-5, the consumption of which, as noted earlier in the text, ranges from 0 to 1 % of the mass of the mixed binder.

Research results. To determine the combined effect of mechanical activation, as well as the addition of ground quartz sand to cement and the consumption of superplasticizer SP-5 on the strength of cement stone at the age of 3, 7 and 28 days, a 2-factor experiment was conducted. The following were taken as independent variables: X_1 – consumption of ground quartz sand (45±15) % of the mass of the mixed binder; X_2 – amount of superplasticizing additive SP-5 (0.5±0.5) % of the mass of the mixed binder. The experimental conditions provided for obtaining for all rows of the mathematical plan mixtures with a spread diameter of 120 mm on the Suttord device (control), Table 1.

Table 1 – Experimental plan and component costs

№	Levels of variation		Consumption of cement dough components per batch, g				W/S	Spread of cement paste, mm	
	X_1	X_2	Portland cement, g	Ground sand, g	SP-5, g	Mixing water, g		Control	Mechanical activation
1	-1	-1	1400	600	0	757	0.38	122	139
2	-1	0	1400	600	10	672	0.34	120	145
3	-1	1	1400	600	20	623	0.31	120	156
4	0	-1	1100	900	0	736	0.37	119	137
5	0	0	1100	900	10	640	0.32	120	141
6	0	1	1100	900	20	582	0.29	118	151
7	1	-1	800	1200	0	720	0.36	120	136
8	1	0	800	1200	10	617	0.31	121	140
9	1	1	800	1200	20	579	0.30	122	148

Analysis of the experimental data given in Table 1, indicates that mechanical and chemical activation for 2 minutes of cement-containing compositions with the addition of ground quartz sand (45±15% of the mass of the mixed binder) contributes to an increase in the diameter of the spread of the mixture (compared to the control) by an average of 14…21 %.

The results of the compressive strength of cement stone at 3, 7, and 28 days of age for both the mechanically activated mixed binder and the binder that was not subjected to mechanical activation (control) are given in Table 2.

Table 2 – Experimental design and compressive strength of cement stone at 3, 7 and 28 days of age

№	Levels of variation		Reviews					
			$R_{cs}^{c.}$, MPa			$R_{cs}^{m.}$, MPa		
	X_1	X_2	3 days	7 days	28 days	3 days	7 days	28 days
1	-1	-1	20.1	32.3	44.5	26.4	43.2	61.1
2	-1	0	24.2	36.6	51.2	33.5	48.2	68.2
3	-1	1	26	40.3	57.4	36.2	54.3	75.5
4	0	-1	15.8	23.4	33.9	20.3	32.7	45.6
5	0	0	18.5	28.5	40.1	24.6	36.9	51.2
6	0	1	21	32.1	46.1	29.7	42.4	60.4
7	1	-1	12.7	21.1	28.8	16.4	28.4	40.2
8	1	0	15.3	23.6	33.3	21.1	32.3	45.1
9	1	1	17.1	27.0	38.1	23.9	36.1	51.4

Note: $R_{cs}^{c.}$, – strength of cement stone on mixed binder, which was not subject to mechanical activation, MPa $R_{cs}^{m.}$, – strength of cement stone on mechanically activated mixed binder, MPa.

As a result of statistical processing of experimental data, mathematical models (1…6) were obtained, which with high probability (≥0,95) reflect the influence of the studied factors on the compressive strength of cement stone both on ordinary (non-mechanically activated) mixed binder (1-3) and on mechanically activated mixed binder (4-6):

$$R_{cs}^{c.3} \text{ (MPA)} = 18.8 - 4.2\ X_1 + 0.8\ X_1^2 + 2.6\ X_2 - 0.6\ X_2^2 \quad (1)$$

$$R_{cs}^{c.7} \text{ (MPA)} = 28.3 - 6.3\ X_1 + 2.2\ X_1^2 - 0.5\ X_1X_2 + 3.8\ X_2 - 0.2\ X_2^2 \quad (2)$$

$$R_{cs}^{m.28} \text{ (MPA)} = 51.8 - 11.4\ X_1 + 4.5\ X_1^2 - 0.9\ X_1X_2 + 6.7\ X_2 + 0.9\ X_2^2 \quad (3)$$

$$R_{cs}^{m.3} \text{ (MPA)} = 25.7 - 5.8\ X_1 + 1.4\ X_1^2 - 0.6\ X_1X_2 + 4.5\ X_2 - 0.9\ X_2^2 \quad (4)$$

$$R_{cs}^{m.7}\ (MPA) = 37.1 - 8.2\ X_1 + 3.1\ X_1^2 - 0.9\ X_1X_2 + 4.8\ X_2 + 0.4\ X_2^2 \quad (5)$$

$$R_{cs}^{c.28}\ (MPA) = 40.0 - 8.8\ X_1 + 2.2\ X_1^2 - 0.9\ X_1X_2 + 6.1\ X_2 - 0.6\ X_2^2 \quad (6)$$

де: $R_{cs}^{c.3}, R_{cs}^{c.7}, R_{cs}^{c.28}$– compressive strength of cement stone on a mixed binder that was not subject to mechanical activation, MPa;

$R_{cs}^{m.3}, R_{cs}^{m.7}, R_{cs}^{m.28}$– compressive strength of cement stone on mechanically activated mixed binder, MPa.

Analyzing mathematical models (1…6), it should be noted that the content of ground sand in the mixed binder has a significant impact on the strength of cement stone both on mechanically activated mixed binder and on mixed binder that was not subjected to mechanical activation. An increase in the amount of ground sand in the mixed binder from 30 to 60 % (mechanical activation is absent) contributes to a decrease in the strength of cement stone from 44.5 MPa to 28.8 MPa, i.e. by almost 35 % (superplasticizer is absent). For cement stone on mechanically activated binder, an increase in the amount of ground sand from 30 to 60 % also causes a decrease in the strength of cement stone, but from 61.1 to 40.2 MPa. It should be determined that in this case, mechanical activation contributes to an increase in the strength of cement stone from 28.8 MPa (control) to 40.2 MPa, i.e. more than 28%. The combined use of mechanical activation and 1% superplasticizer ensures the obtaining of a compressive strength of cement stone at 28 days of age of 75.5 MPa (with 60 % ground sand in the mixed binder), i.e. almost 24 % higher compared to the control.

Considering the influence of variable factors on the compressive strength of cement stone, it should be noted that mechanical activation of mixed cement in combination with the use of superplasticizer SP-5 allows changing the compressive strength of cement stone in a wide range at 3, 7 and 28 days of age.

A graphical representation of the influence of factors X_1 and X_2 on the strength of cement stone at 28 days of age is shown in Fig. 1.

Table 3 and Table 4 show the values of the factors X_1 and X_2, which provide the greatest strength of the stone in the studied stone (28 days).

Analysis of the influence of the formulation factors X_1 and X_2 on the strength of the stone on the binder, which was subjected to mechanical activation and non-mechanically activated binder (control) shows that by changing the influencing factors (mechanochemical activation, consumption of ground quartz sand and concentration of superplasticizer) it is possible to regulate the compressive strength of the cement stone at 28 days of age in the range from 25.8 (control) to 74.5 MPa.

The experimental results obtained indicate that:

a) mechanical and chemical activation of the aqueous cement-containing composition with the addition of ground quartz sand (45±15 %) provides an increase in the diameter of the spread of the mixture by an average of 14…21 % (compared to the control);

b) activation of mixed Portland cement in the presence of superplasticizer SP-5 (1 %) provides an increase in the strength of cement stone in the studied period of time (3, 7 and 28 days) on average by 2.5….2.9 times (compared to the control).

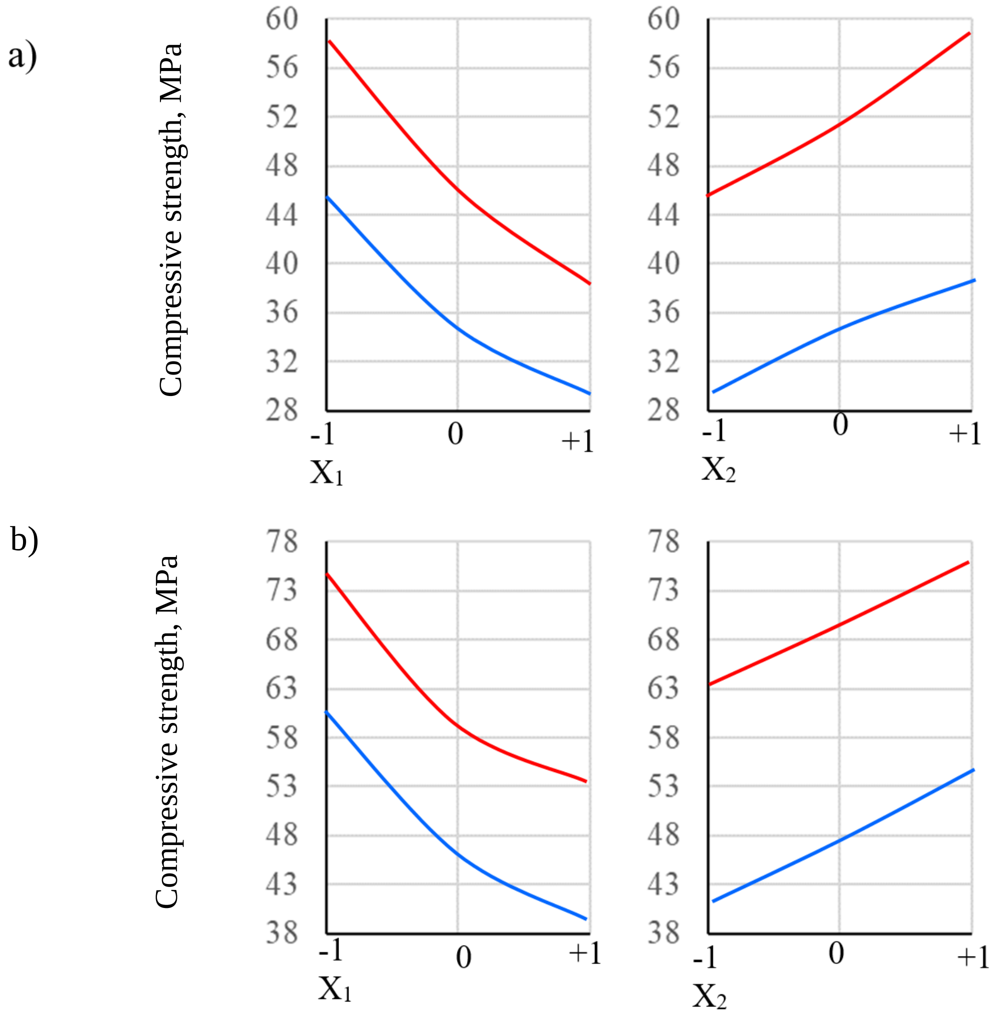

Fig. 1. Strength of cement stone at 28 days of age in the zone of maximum and minimum depending on the factors X_1 and X_2:
a – control-mixed binder that was not subject to mechanical activation; б – mixed mechanically activated binder. (blue line) – zone of maximum strength; (red line) – minimum strength zone

Table 3 – Values of recipe factors X_1, which are responsible for the maximum and minimum strength (MPa) of cement stone

	Mechanical activation of the binder is absent (control) at the age of 3, 7 and 28 days of hardening								
	3 days		R_{cs}^{3}	7 days		R_{cs}^{7}	28 days		R_{cs}^{28}
	X_1	X_2		X_1	X_2		X_1	X_2	
min	+1	-1	12.6	+1	-1	20.7	+1	-1	25.8
max	-1	+1	26.2	-1	+1	40.9	-1	+1	55.6

Table 4 – Values of recipe factors X_2, which are responsible for the maximum and minimum strength (MPa) of cement stone

	Mechanically activated binder at 3, 7 and 28 days of hardening								
	3 days		R_{cs}^{3}	7 days		R_{cs}^{7}	28 days		R_{cs}^{28}
	X_1	X_2		X_1	X_2		X_1	X_2	
min	+1	-1	16.5	+1	-1	28.5	+1	-1	39.9
max	-1	+1	37.1	-1	+1	54.5	-1	+1	74.5

Conclusions. The combined effect of activation of Portland cement and the addition of quartz sand with a specific surface area of 350 m^2/kg in an amount of 30 to 60 % of the mass of the mixed binder and the addition of superplasticizer SP-5 is an effective recipe-technological effect that provides a significant increase in the compressive strength of cement stone both at an early age (3 days) and at a more mature age (28 days). The combined use of mechanical activation and superplasticizer SP-5 significantly eliminates the loss of strength of cement stone due to the use of ground sand additives to cement in an amount of 30 to 60 %.

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ВПЛИВ МЕХАНОАКТИВАЦІЇ ЗМІШАНОГО ПОРТЛАНДЦЕМЕНТУ В ПРИСУТНОСТІ СУПЕРПЛАСТИФІКАТОРУ НА МІЦНІСТЬ НА СТИСК ЦЕМЕНТНОГО КАМЕНЮ

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Анотація. В розглянутій статті приводяться експериментальні результати, які пов’язані з визначенням впливу механоактивації змішаного портландцементу та суперпластифікуючої добавки $SP-5$ на фізико-механічні харектиристики цементного каменю на стиск у віці 3-х, 7-и та 28-и діб. Такий цемент отримували змішуванням портландцементу ПЦ-І 500 з меленим кварцовим піском $(S = 350\ м^2/кг)$, кількість якого коливалася в діапазоні від 30 до 60 % в'яжучого. Перспективним способом підвищення міцності цементного каменю на стиск є інтенсивна механохімічна активація змішаного цементу у швидкісному активаторі турбулентного типу за присутності суперпластифікатора *SP-5*, вміст якого змінювався в межах від 0 до 1 % маси в’яжучої речовини.

Дослідження здійснювали із застосуванням D-оптимального математичного планування експерименту з варіюванням наступних факторів: X_1 – витрата меленого кварцового піску (45±15) % від маси комбінованого в’яжучого матеріалу; X_2 – кількість суперпластифікуючої добавки $SP-5$ – $(0,5 \pm 0,5)$ % маси змішаного в’яжучого. Приготування цементно-водної суміші проводилося за двома технологіями ,а саме: першої – з використанням швидкісного активатору з кількістю обертів ротору 1500 об/хв і другої , традиційної (контроль). Отримані математичні моделі вказують на суттєвий вплив на міцність цементного каменю як рецептурних факторів (X_1, X_2), так і технологічних параметрів процесу приготування суміші. Зокрема слід відзначити, що сумісний вплив механохімічної активації, витрати меленого піску та суперпласифікатору дозволяє підвищити міцність цементного каменю в (в порівнянні з контролем) на 22…41 %), що дає змогу суттєво збільшити частку меленого кварцового піску у складі змішаного в’яжучого як мінеральної добавки до цементу.

Ключові слова: механоактивація, портландцемент, суперпластифікатор, мінеральна добавка, міцність на стиск, фактори варіювання.

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ПІДВИЩЕННЯ ЕФЕКТИВНОСТІ ТЕМПЕРАТУРНОГО РОЗПОДІЛУ ЗА ДОПОМОГОЮ ЗАКРУЧЕНОГО ПОВІТРЯНОГО СТРУМЕНЯ

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Анотація. Ефективне керування тепловими процесами в повітряних потоках є важливою умовою підвищення енергоефективності вентиляційних і теплотехнічних систем. Метою дослідження є аналіз процесів зниження надлишкової температури в ізотермічному вільному закрученому повітряному струмені з подальшим удосконаленням підходів до регулювання теплових характеристик потоку. Актуальність роботи зумовлена потребою підвищення енергоефективності вентиляційних систем та теплотехнічного обладнання шляхом оптимізації температурних полів. Основне завдання полягало в аналізі процесів теплового згасання, обчисленні відповідного коефіцієнта та побудові температурних профілів у поперечних перерізах струменя. Для спрощення математичного опису введено коефіцієнт затухання температури, що дозволяє більш наочно оцінити динаміку теплового розсіювання. Здійснено кількісне дослідження розподілу осьових температур, побудовано графіки залежностей та визначено характер змін у різних зонах струменя. Запропоновано ефективний спосіб обчислення відносних температурних значень у довільних поперечних перерізах. Для врахування впливу гравітаційної сили на розвиток термічного поля застосовано безрозмірний критерій Архімеда. Температурні розподіли в струмені описано на основі узагальненої аналітичної моделі, аналогічної моделі Шліхтінга, адаптованої до теплових задач. Результати дослідження подано у вигляді узагальнених графічних залежностей та формул із поправочними коефіцієнтами. Виконано зіставлення експериментальних спостережень з результатами аналітичного моделювання, що засвідчило високу відповідність між отриманими даними та теоретичними передбаченнями. Проведений аналіз також охоплює формування турбулентних теплових структур у процесі охолодження струменя. Показано можливість регулювання температурного профілю шляхом зміни граничних умов та початкових параметрів. Отримані висновки можуть бути ефективно застосовані у проєктуванні вентиляційних систем, теплотехнічного обладнання та енергетичних агрегатів, де критичною є рівномірність розподілу температури в повітряному середовищі. Зазначені результати є підґрунтям для подальшого дослідження нелінійних ефектів теплопередачі в умовах дії зовнішніх збурень та допоможуть розробити алгоритми автоматичного керування мікрокліматом у замкнених просторах.

Ключові слова: аеродинаміка, турбулентні потоки, закручений струмінь, температура, надлишкова температура, коефіцієнт затухання температури.

Вступ. Раціональний розподіл температурного поля у внутрішніх приміщеннях є ключовим чинником для формування сприятливого мікроклімату, підвищення енергоефективності та стабільної роботи систем повітрообміну [1]. Стандартні способи подачі повітря не завжди забезпечують необхідну однорідність температурного середовища, що може спричинити виникнення термічних застійних зон або нерівномірність теплових потоків [2].

Одним із перспективних рішень є застосування закручених повітряних струменів, які характеризуються підвищеним ступенем перемішування та стабільнішим поширенням теплового навантаження в об'ємі приміщення. Такі струмені демонструють збереження температурного надлишку на більших відстанях та сприяють рівномірному розподілу тепла [3, 4]. У зв'язку з цим особливого значення набуває дослідження ізотермічного вільного закрученого повітряного струменя як об'єкта, що дозволяє розкрити особливості формування й розвитку температурного поля у повітряному середовищі.

Аналіз останніх досліджень та публікацій. У дослідженні [5] проаналізовано вплив геометрії вентиляційного отвору та режиму подачі припливного повітря на формування структури повітряного струменя. Автори зосередили увагу на різновидах потоків – плоских, осесиметричних і закручених – які виникають залежно від конфігурації сопла та умов подачі повітря, однак, не розглянуто теплові особливості закрученого струменя та процес його температурного затухання. У роботі [6] розглянуто вплив навколишніх поверхонь на режим розвитку повітряного струменя. Установлено, що за відсутності перешкод потік є вільним, а у випадку взаємодії з твердими межами – обмеженим. Це має суттєве значення для оцінки теплових та аеродинамічних характеристик струменя, але у роботі не подано аналітичного опису температурного поля у вільному закрученому струмені. У статті [7] проаналізовано класифікацію струменів за температурним режимом. Зокрема, наголошено на важливості розмежування між ізотермічними та неізотермічними потоками, що дозволяє точніше передбачати їхню поведінку в реальних умовах експлуатації вентиляційних систем. Однак, не подано математичного опису температурного затухання та розподілу температури в ізотермічному закрученому потоці. У дослідженні [8] визначено ключову роль числа Рейнольдса для класифікації режимів руху повітря. Наведено критичні значення Re, що дозволяють розмежувати ламінарні й турбулентні режими, а також проаналізовано вплив турбулентності на інтенсивність теплового обміну. Проте, не розглянуто детально механізми формування турбулентних теплових структур у закрученому струмені. У роботі [9] розглянуто формування ядра струменя, в якому зберігаються початкові параметри потоку. Запропоновано методику визначення зони поширення температурного впливу шляхом побудови зовнішнього контуру струменя через геометричну прив'язку до осі симетрії, але не враховано вплив гравітаційних сил на розподіл температури. У статті [10] проаналізовано теплові процеси в початковій зоні неізотермічного струменя. Автори підкреслюють наявність теплового затухання вздовж осі симетрії та значну інтенсивність теплообміну із зовнішнім середовищем, що визначає специфіку розвитку струменя на ранніх етапах його поширення. Проте не запропоновано формального коефіцієнта температурного затухання та не подано узагальненої аналітичної моделі для опису температурного поля.

Таким чином, огляд сучасної літератури засвідчив комплексне вивчення геометричних, гідродинамічних і теплових характеристик повітряних струменів. Проте жодна з проаналізованих робіт не зосереджена на кількісному описі процесів затухання температури саме в ізотермічному вільному закрученому струмені з урахуванням критеріїв подібності та корекційних коефіцієнтів. Це і визначає актуальність проведення нашого дослідження.

Мета та завдання. Предметом цього дослідження є закономірності розподілу температури та особливості згасання теплових характеристик в межах вказаного потоку. Метою роботи є аналіз просторової динаміки температури в закрученому струмені з подальшим удосконаленням методичних підходів до регулювання теплових параметрів повітряних систем.

Для досягнення поставленої мети визначено такі основні завдання дослідження:

1. Провести аналіз формування температурного поля в ізотермічному закрученому струмені.

2. Визначити аналітичну залежність для опису процесу теплового згасання.

3. Ввести коефіцієнт затухання температури як узагальнюючий параметр для оцінювання динаміки розсіювання тепла.

4. Побудувати температурні профілі у поперечних перерізах струменя та дослідити їхню зміну вздовж осі.

5. Застосувати безрозмірні критерії (зокрема Архімеда) для врахування впливу гравітації на розподіл температури.

6. Порівняти отримані аналітичні результати з експериментальними спостереженнями для підтвердження достовірності моделі.

Аналіз теплових властивостей закручених потоків дозволяє глибше осмислити механізми їх формування, що, у свою чергу, створює передумови для вдосконалення методів керування тепловими процесами. Це має важливе значення для проєктування ефективних систем вентиляції, кондиціонування та теплотехнічного обладнання в промислових і громадських будівлях.

Матеріали та методика дослідження. Залежно від величини критерію Архімеда Ar_0 припливні повітряні струмені класифікують як слабо неізотермічні, якщо гравітаційний вплив на них незначний, та неізотермічні, якщо температура істотно впливає на їхню траєкторію [11].

Як відомо [12], для горизонтальних струменів із малою температурною різницею (слабо неізотермічні) надлишкова температура визначається за формулою (1):

$$\Delta t_x = \frac{N}{x}, \tag{1}$$

де x – координата вздовж осі струменя, а N – узагальнений тепловий параметр, що розраховується за залежністю [13]:

$$N = \frac{0{,}54}{tg\alpha}\sqrt{\frac{T_в}{T_o}} \cdot \frac{1}{\sqrt[4]{\xi}} \cdot \Delta t_o \cdot \sqrt{F_o}, \tag{2}$$

де α – кут розширення струменя (прийнято α = 12°25', відповідно tgα = 0.22); ξ =1 – коефіцієнт місцевого опору; $T_в$ – абсолютна температура повітря на виході з насадки, К; F_0 – площа перерізу насадки, м^2; Δt_0 – початкова надлишкова температура, ^{0}С.

Початкова надлишкова температура розраховується за формулою (3) [13]:

$$\Delta t_0 = T_в - T_o. \tag{3}$$

З метою оптимізації розрахунків вводиться безрозмірний коефіцієнт затухання температури n [13]:

$$n = \frac{0{,}54}{tg\alpha}\sqrt{\frac{T_в}{T_o}} \cdot \frac{1}{\sqrt[4]{\xi}}, \tag{4}$$

де всі позначення відповідають попередньому виразу. Враховуючи це, подовжнє зменшення надлишкової температури на певній відстані x представлено у вигляді (5):

$$\Delta t_x = n \cdot \Delta t_o \cdot \frac{\sqrt{F_o}}{x}. \tag{5}$$

Отримані залежності дозволяють кількісно описати закономірності охолодження струменя та врахувати вплив геометричних і теплових параметрів на процес поширення температурного поля в повітряному потоці [14].

На будь-якій площині перерізу, розташованій на координаті x, величина надлишкової температури $\Delta t_\gamma = t_\gamma - t_v$ на відстані y від осі струменя визначається за модифікованою формулою Тейлора [14]:

$$\Delta t_y = \Delta t_x \cdot \exp\left(-0{,}7\sigma_T \bar{y}^2\right), \tag{6}$$

де σ_T – число Прандтля для турбулентного теплообміну, що для компактних струменів зазвичай змінюється в межах 0.65–0.7; $\bar{y}$ = y/(cx) – відносна поперечна координата; c = 0.28 – емпірична константа, отримана за експериментальними даними, y та x – відповідно поперечна та поздовжня координати, м.

У будь-якому поперечному перерізі (координата «x») та на певній відстані «y» від осі, температура Δt_y обчислюється з урахуванням профілю розподілу за законом:

$$\Delta t_y = t_x\left[1 - \left(\frac{y}{y_b}\right)^{1{,}5}\right]^2. \tag{7}$$

У практиці аналізу температурних полів струменя доцільно застосовувати нормовані значення температурного перевищення як у поздовжньому напрямку:

$$\Delta \bar{t}_x = \Delta t_x / \Delta t_o, \tag{8}$$

так і в поперечному:

$$\Delta \bar{t}_y = \Delta t_y / \Delta t_x . \qquad (9)$$

Ці безрозмірні величини дозволяють уніфікувати аналіз температурного розподілу вздовж і поперек осі струменя для різних геометричних та температурних умов [15].

Середня відносна осьова та поперечна надлишкова температура (відповідно (8)(9)) описуються за допомогою температурних відносних коефіцієнтів (10), [15]:

$$\overline{\Delta t}_x = \frac{0{,}48}{\frac{ax}{d_e} + 0{,}145}, \qquad (10)$$

де a = 0,078, безрозмірна експериментальна константа; d_e – еквівалентний діаметр отвору насадки, м.

Число Архімеда Ar_0 що характеризує баланс між гравітаційними та інерційними ефектами в струмені, визначається за [15]:

$$Ar_o = \frac{g\sqrt{F_o} \cdot \Delta t_o}{t_o^2 \cdot T_в}, \qquad (11)$$

де g = 9.81 m/s²; F_0 – площа виходу насадки (м²); $\Delta t_0 = t_0 - t_v$ – надлишкова температура (^{0}C); $T_в$ – температура повітря в приміщенні (К); t_0 – температура повітря в струмені (^{0}C).

Результати досліджень. Для вимірювань було використано термоелектричний анемометр testo-405. Початкове значення температури t_0. було встановлено експериментально. Значення x_i варіювали в межах 0.7-2.2. Температурні розподіли t_y у поперечному напрямку було розраховано за формулою (10), після чого побудовано графіки залежності $\bar{t}_x = f(\bar{x})$, де $\bar{x} = x/\sqrt{F_o}$.

Результати на рис. 1 добре узгоджуються з теоретичними розрахунками.

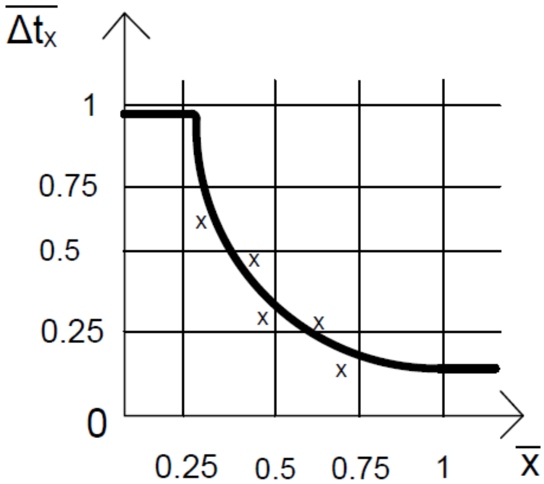

Рис. 1. Залежність відносної осьової надлишкової температури від відносної поздовжньої координати

Отже, внаслідок виконаної роботи можна сформулювати такі наукову новизну та практичну значущість результатів дослідження.

Наукова новизна отриманих результатів дослідження полягає в тому, що вперше для ізотермічного вільного закрученого повітряного струменя введено узагальнений коефіцієнт теплового затухання, який забезпечує спрощене аналітичне представлення процесів розсіювання температури. Побудовано температурні профілі у довільних поперечних перерізах з використанням апроксимуючих функцій, що дозволило уточнити просторову структуру термічного поля. Урахування безрозмірного критерію Архімеда дало змогу розширити існуючі моделі опису теплообміну у вільних струменях за рахунок врахування гравітаційних ефектів.

Практична значущість результатів дослідження полягає в можливості використання отриманих залежностей та коефіцієнтів для інженерного розрахунку теплових характеристик вентиляційних систем, теплотехнічного обладнання та енергетичних установок. Запропоновані моделі дозволяють заздалегідь прогнозувати розподіл температури повітря в приміщенні, забезпечуючи ефективніше проєктування систем мікроклімату з урахуванням рівномірності температурного поля та енергоефективності.

Висновки. За результатами проведеного дослідження можна сформулювати такі основні висновки:

1. Отримані результати сприяють удосконаленню підходів до аналізу теплових характеристик повітряних потоків і є необхідними при проєктуванні вентиляційних систем.
2. Встановлено характер розподілу відносної осьової надлишкової температури в повітряному закрученому струмені.
3. Визначено закономірності зміни відносної осьової надлишкової температури вздовж осі.
4. Проведене порівняння експериментальних даних із результатами аналітичного моделювання підтверджує надійність запропонованого математичного опису та доцільність його використання у практичних застосуваннях, зокрема в теплотехніці, вентиляції та енергетиці.

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IMPROVING TEMPERATURE DISTRIBUTION EFFICIENCY USING A SWIRLING AIR JET

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Abstract. Effective control of thermal processes in air flows is an important condition for improving the energy efficiency of ventilation and heat engineering systems. The aim of the study is to analyze the processes of reducing excess temperature in an isothermal free swirling air jet, followed by the improvement of approaches to regulating the thermal characteristics of the flow. The relevance of the work is determined by the need to enhance the energy efficiency of ventilation systems and heat engineering equipment through the optimization of temperature fields. The main task consisted in analyzing the processes of thermal decay, calculating the corresponding coefficient, and constructing temperature profiles in cross-sections of the jet. To simplify the mathematical description, a temperature attenuation coefficient was introduced, which makes it possible to more clearly assess the dynamics of heat dissipation. A quantitative study of axial temperature distribution was carried out, dependence graphs were constructed, and the nature of changes in different jet zones was determined. An efficient method for calculating relative temperature values in arbitrary cross-sections was proposed. To account for the influence of gravitational forces on the development of the thermal field, the dimensionless Archimedes number was applied. The temperature distributions in the jet were described on the basis of a generalized analytical model similar to the Schlichting model, adapted to thermal problems. The results of the study are presented in the form of generalized graphical dependencies and formulas with correction coefficients. A comparison of experimental observations with analytical modeling results demonstrated a high degree of agreement between the obtained data and theoretical predictions. The analysis also covers the formation of turbulent thermal structures during jet cooling. The possibility of regulating the temperature profile by changing boundary conditions and initial parameters is shown. The obtained conclusions can be effectively applied in the design of ventilation systems, heat engineering equipment, and energy units, where the uniformity of temperature distribution in the air environment is critical. The presented results provide a foundation for further research on nonlinear heat transfer effects under external disturbances and will contribute to the development of algorithms for automatic microclimate control in enclosed spaces.

Keywords: aerodynamics, turbulent flows, swirling jet, temperature, excess temperature, temperature attenuation coefficient.

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ARCHITECTURE OF AN AUTONOMOUS INTELLIGENT SYSTEM FOR MANAGING CONSTRUCTION PROCESSES UNDER THE RISK OF EXTERNAL IMPACTS

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Abstract. This paper explores the problem of ensuring the autonomy and fault tolerance of intelligent control systems used in construction process management under conditions of external risks, such as power outages, loss of network connectivity, or cyber-attacks. As artificial intelligence (AI) becomes increasingly involved in construction scheduling, monitoring, and resource coordination, there is a pressing need to develop system architecture capable of maintaining critical functionality under infrastructure failures. The main objective of this research is to design and formalize a model of an autonomous AI-driven system that can operate independently from centralized infrastructure and seamlessly transition to fallback control logic when needed.

The methodology combines system architecture analysis, the use of UML diagrams (use case, component, and state diagrams) to model functional logic and interactions, risk scenario modeling using failure analysis techniques, and a comparative evaluation of centralized and edge-based computing approaches. The proposed three-layer architecture (physical, computational, and communication) is centered on a local edge server. This server hosts AI modules, handles anomaly detection, power switching, and provides decision-making capacity independently of cloud services.

The results demonstrate that the implementation of a hybrid autonomous control system significantly enhances the resilience of construction operations. The edge-based architecture outperforms centralized models in response time, offline operability, and stability in unstable environment. A comparative analysis shows that the deployment of such a system may increase initial costs by 5–10%, yet these costs are justified by a substantial reduction in risk of downtime, delays, and data loss.

The proposed system is particularly suitable for construction sites operating in constrained or high-risk conditions, including strategic infrastructure projects or military-affected zones. Future research should focus on optimizing AI algorithms for offline operation, developing industry-wide integration protocols, and validating the proposed model through real-life implementation in pilot projects.

Keywords: artificial intelligence, construction management, autonomous systems, edge computing, fault tolerance, system architecture, risk modeling, digital twins, UML diagrams.

Introduction. Modern construction enterprises are increasingly implementing artificial intelligence (AI) technologies to automate processes of planning, monitoring, equipment and resource management. In this paper, the term *"system architecture"* refers to the structural and logical organization of an intelligent management system. However, most of these systems operate dependent on external energy sources, internet connectivity, or cloud data processing, making them vulnerable to failures, cyber-attacks, or energy crises. Under conditions of hybrid threats and instability, it is essential to develop backup infrastructure and algorithms for rapid switching to alternative control systems that ensure continuity of construction [1-4].

*Problem statement***.** Despite significant progress in the implementation of artificial intelligence in construction, the issues of autonomy and resilience of such systems remain insufficiently addressed in the scientific and applied literature [3, 5–7]. The structure of an intelligent construction management system capable of functioning under conditions of complete loss of external resources (electricity, internet, cloud infrastructure) remains an open question. Another challenge is determining the architecture of a backup parallel system should look like.

Despite considerable advances in the use of information modeling and automation of construction processes, the problem of insufficient integration of real-time risk management systems persists.

The expected technical and economic effect of developing an autonomous intelligent management system includes:

- reduction of construction process duration through event-driven management;
- decrease of avoidable costs (equipment downtime, delays due to weather or organizational factors);
- improvement of resource planning accuracy and scheduling.

The potential scope of application covers: residential and commercial construction projects employing BIM technologies; infrastructure projects implemented in high-risk conditions (e.g., military or recovery projects); public procurement, where transparent and digitally supported management systems are required.

Thus, the creation of architecture for an autonomous intelligent management system has not only scientific novelty but also significant socio-economic potential.

However, it should be noted that such a system can operate only under conditions of sufficiently advanced adoption of modern digital technologies. At present, this also remains a challenge for the construction industry in Ukraine.

Analysis of Recent Research and Publications. At present, research in the field of construction automation is primarily focused on the implementation of BIM + AI; schedule and resource management through ML models; digital twins of processes; and improving the energy efficiency of construction sites. However, backup parallel architectures and system-switching algorithms for AI under threat conditions remain almost unexplored, especially in the context of construction in regions with unstable infrastructure [8–11].

Article [12] presents the concept of a decentralized autonomous construction management system that integrates digital twins, large language models, and decentralized autonomous organizations to create self-managed buildings. Study [13] is devoted to analyzing the potential of artificial intelligence in construction, emphasizing the importance of transparency and trust in intelligent systems within the industry.

A systematic review [14] highlights the application of AI across all stages of the construction project life cycle, with particular focus on risk management and decision-making. Article [15] explores the issue of trust in artificial intelligence and robotics in architecture, engineering, and construction, underlining the necessity of developing reliable systems that are beneficial throughout all phases of project implementation.

Work [16] provides a comprehensive review of risk management research in construction, with an emphasis on integrating information and communication technologies and AI to enhance risk management practices.

Despite significant progress in the implementation of AI and autonomous systems in construction, several unresolved issues remain:

1. Integration of decentralized management systems**.** The application of decentralized autonomous organizations in construction for improving flexibility and resilience of management systems remains insufficiently studied.

2. Explainability and trust in AI**.** There is a need to develop transparent AI algorithms that ensure decision-making processes are understandable to users and stakeholders.

3. Risk management under external influences. Adaptive systems must be created to respond promptly to external threats such as natural disasters or cyber-attacks.

4. Standardization and regulation**.** The absence of unified standards and regulations for the implementation of autonomous intelligent systems in construction complicates their widespread adoption.

Aim and Objectives of the Article. The aim of this study is to develop a conceptual architecture of an autonomous and fault-tolerant intelligent management system for construction processes, including a description of functional modules, scenarios of switching to backup control, and an analysis of the impact on project economics.

The main research objectives are as follows:

1. To analyze current approaches to the development of intelligent management systems in construction, considering external risks (power outages, loss of connectivity, cyber threats, etc.).
2. To design a functional system architecture that includes key modules: AI core, energy control units, anomaly detection, fallback controller, and user interface.
3. To formalize the system's operational logic using UML diagrams – use case, component, and state diagrams – for modeling behavior under both normal and emergency conditions.
4. To conduct a scenario-based analysis of switching to backup control, considering typical risks and activation criteria for autonomous mode.
5. To perform a comparative analysis of centralized and edge-based architectures in terms of technical, operational, and economic indicators.
6. To evaluate the economic feasibility of implementing a backup autonomous architecture within a construction project, taking into account potential losses, downtime, and infrastructure costs.

Materials and Research Methodology. The research methodology is based on an interdisciplinary approach that combines systems analysis, engineering modeling, and elements of software architecture, risk analysis, and economic evaluation. The main tools applied include:

- UML diagrams**:** in particular, Use Case, Component, and State diagrams, which are employed to formalize the functional architecture of the Autonomous Intelligent Control System (AICS).
- Architectural modeling**:** analysis of centralized and decentralized (edge-based) control structures, with the development of a three-layer model (physical, computational, and communication levels).
- Scenario modeling**:** development of scenarios of critical external impacts (power outage, cyber-attack, loss of connectivity), accompanied by the design of an algorithm for emergency switching to a Reserve Hybrid Control System (RHCS).
- Fault-tolerance analysis methods**:** assessment of system response time, identification of bottlenecks, and determination of minimum technical requirements to ensure autonomous operation.
- Techno-economic feasibility tools (TEF): analysis of the costs of implementing backup infrastructure and its impact on the overall efficiency of the construction process.

The research foundation consists of:

- results of the authors' previous publications highlighting organizational and technical aspects of AI applications in construction;
- data on edge-server configurations, backup power sources (UPS, generators), and sensor infrastructure;
- practical case studies from construction management under limited infrastructure conditions (including during armed conflict);
- existing open libraries of predictive models for machine learning (ML) and computer vision (CV), adapted for autonomous execution on edge devices.

Thus, the chosen methodology makes it possible not only to simulate the system's behavior under stress conditions but also to propose practical architectural solutions capable of ensuring the resilience of construction processes under external threats.

Research Results. In critical infrastructures such as a construction enterprise partially managed by artificial intelligence, emergency response scenarios and backup control channels must be strictly regulated. Below, we present the concept of a parallel (backup) system to AI and the algorithm for switching to it in the event of power failures. This system is referred to as the *"Reserve Hybrid Control System (RHCS)"*.

Its primary purpose is to ensure continuity of critical construction processes in the event of AI system failure. The system requires a set of essential components for its operation (Fig. 1).

Consider a scenario that may occur during construction operations. Concrete works are in progress on a construction site. During the process, power supply is lost, and the primary AI system stops functioning. Immediately after this: the UPS is activated; a signal is sent to the smartphones of on-duty engineers; the backup control system is launched; the operator receives a notification and connects to the console; in manual mode, the operator activates concrete mixers and initiates concrete supply via the local controller. Figure 2 illustrates the proposed algorithm of emergency switching to the RHCS (with a conditional trigger: loss of main power supply / AI system failure).

For the operation of such an autonomous system, the following recommendations can be proposed: the presence of a regulation clearly defining responsibilities in case of an emergency; monthly testing of the switchover to the backup system; storing the latest version of the working plan offline; and training personnel to work with the RHCS.

To ensure that an artificial intelligence system within a construction enterprise operates autonomously – thus minimizing dependency on external factors such as electricity, communication networks, or cloud access – it is necessary to implement a resilient autonomy architecture.

An equally important aspect of the proposed architecture is its economic feasibility. Practical calculations and results of international studies demonstrate that investments in digital infrastructure at a level of approximately 5% of the estimated project cost can yield proportional or even greater reductions in indirect expenditures. These savings primarily stem from reducing losses associated with documentation inconsistencies, rework, delays in managerial decision-making, and inefficient use of resources. In the case of large-scale residential or infrastructure projects, the potential economic impact may reach tens of millions of hryvnias, which confirms the rationale for the phased implementation of intelligent management systems in construction practice.

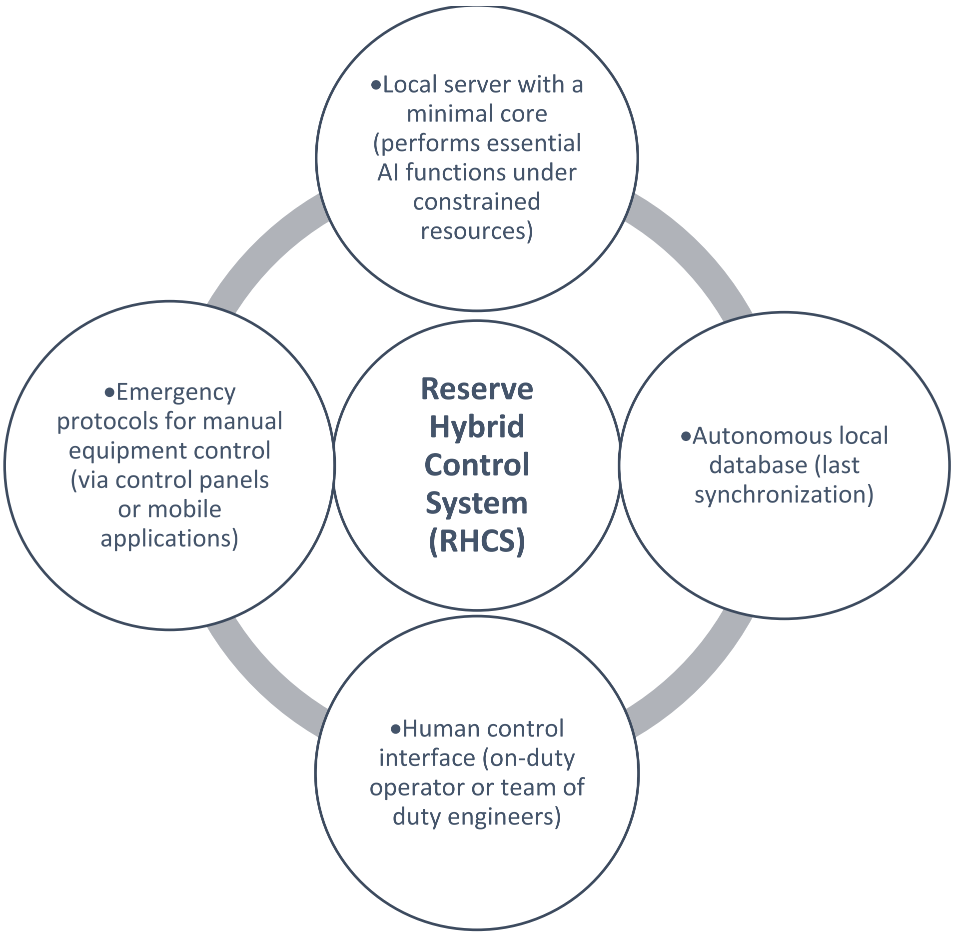

Fig. 1. Components of the Reserve Hybrid Control System (RHCS)

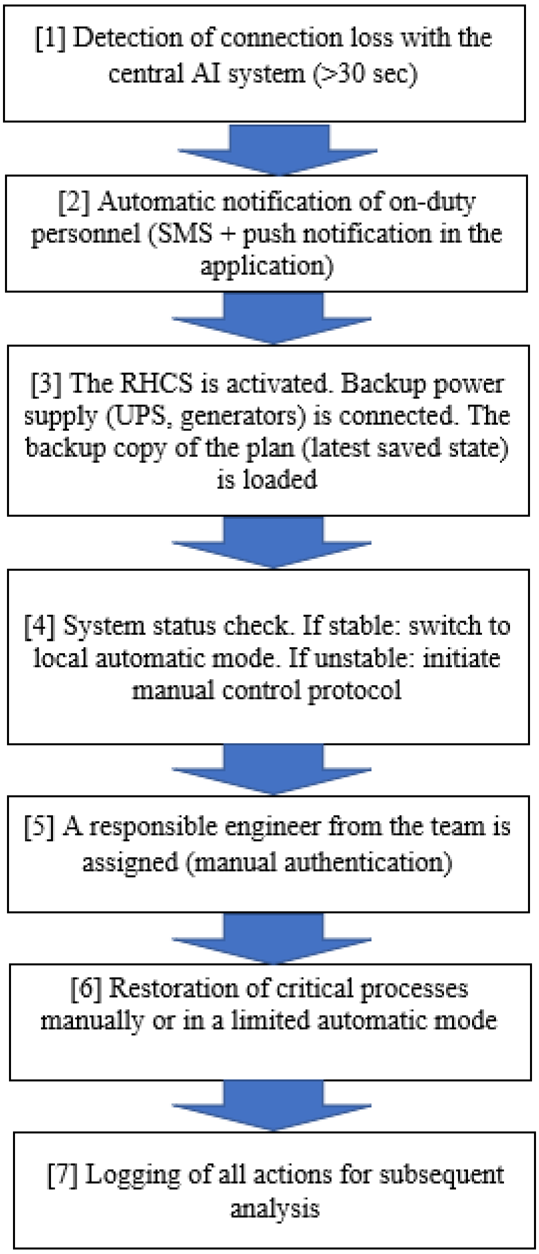

Fig. 2. Algorithm of emergency transition to RHCS (trigger condition: loss of main power supply / AI system failure)

At the same time, it is important to emphasize that a fallback scenario based on a complete reversion to manual management relying solely on construction specialists cannot be considered an effective alternative. This limitation is explained by the high complexity of modern projects, the multichannel nature of information flows, and the dynamic character of external factors (climatic, economic, regulatory). Under such conditions, manual control does not provide the required speed of reaction, transparency of decision-making, or adequate risk forecasting. Therefore, the backup approach should not mean abandoning digitalization, but rather the development of hybrid models that combine partial expert involvement for AI decision verification with automated processes, thereby integrating technological efficiency with human expertise.

Considering the presented response algorithm, it is reasonable to highlight the key technical solutions that form the foundation of the autonomy architecture of the intelligent system. A summary of these solutions is provided in Table 1.

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Table 1 – Technical solutions for enhancing the autonomy of AI-based construction systems

Technical Solution	Explanation
1. Local computational infrastructure	Deployment of edge servers (on-site computing units with AI cores independent of the Internet)
	Storage of critical models and datasets directly at the construction site
2. Intelligent backup power supply	High-capacity uninterruptible power supply (UPS) systems with batteries providing at least 6–12 hours of autonomy
	Hybrid energy supply: solar panels + diesel generators + batteries
	Smart energy consumption monitoring and control
3. Modular AI system architecture	Separation into independent functional modules (e.g., equipment control, safety monitoring, scheduling) capable of operating autonomously in the event of partial system failure
4. Offline model duplicates	Copies of machine learning models and decision scenarios functioning without cloud connectivity
	Local updates applied with a delay via flash memory or internal secured networks.
5. Resilient communication	Deployment of a local private LTE/5G network, radio communication, or mesh networks to minimize dependence on external providers

To assess the feasibility of implementing the proposed technical solutions, an approximate calculation of additional costs for their integration into a typical construction project was performed. The results are presented in Table 2.

Table 2 – Approximate cost increase per project

Category	Estimated cost, $	Approximate increase in project cost
Edge servers + AI modules	10.000 – 30.000	+1–2% of the project budget
Backup power supply (UPS, generator, solar panels)	15.000 – 50.000	+2–4%
Local networks, communication	5.000 – 15.000	+1%
Deployment and integration	10.000 – 25.000	+1–2%

The overall increase in project cost is estimated at 5–10%, while at the same time:

– Risks of downtime, accidents, and incidents are reduced.

– Predictability and controllability of the construction process are improved.

– Staff requirements can be reduced at certain stages.

A more detailed consideration of the Reserve Hybrid Control System (RHCS) is provided below. To ensure stable operation of the intelligent construction management system even in cases of critical failures (e.g., power outages or loss of connectivity with cloud services), it is advisable to formalize the system's architecture in the form of a component model. Given the complexity of the system and the need for its formalization for modeling and implementation, the functional decomposition of the architecture into key levels is presented in Table 3.

Table 3 – Key system levels

Level	Function description
1. Physical level (construction site)	Sensors, detectors, video cameras, drones, controllers, generators, energy sources (grid/UPS/generator)
2. Computational level (local edge server)	Execution of AI algorithms (ML, CV, NLP), equipment control, predictive models, autonomous control systems
3. Communication level	API connection with cloud services or backup local channel (Wi-Fi mesh, radio channel).

The key element of the proposed autonomous intelligent system is the edge server, which acts as the local control core. Its functional purpose is to ensure the uninterrupted operation of the AI system under conditions of disconnection from cloud computing services. This allows the system to maintain critical functionality, including decision-making, emergency monitoring, and generating appropriate responses, even when operating in isolation from external sources.

To describe the system's functional logic, two key UML diagrams are applied: the Use Case Diagram and the Component Diagram.

The Use Case Diagram illustrates the interaction between the user and the system, focusing on the main usage scenarios. The user in this case may be either an operator or an external control entity (e.g., a Telegram bot or an ERP/BIM control module).

The main scenarios include:

- Automatic updating of the construction schedule based on changes in resources or execution conditions.
- Response to emergency situations, such as logistics delays, loss of access to equipment, or critical data.
- Intelligent switching between power supply channels, including automatic selection between the grid, generator, or UPS.
- Generating alerts for the user, with the ability to deliver notifications through a visual interface or a Telegram bot.

The Component Diagram, on the other hand, represents the software–hardware architecture that implements the mentioned functions. It demonstrates the structural organization of the system and the interconnections between its modules, such as: the AI Engine**,** Task Scheduler**,** Energy Control Module**,** Anomaly Detector, and the Fallback Controller. The central element is the edge server, which provides integration between software modules and hardware devices, including the UPS Module and the Operator Terminal (Fig. 3).

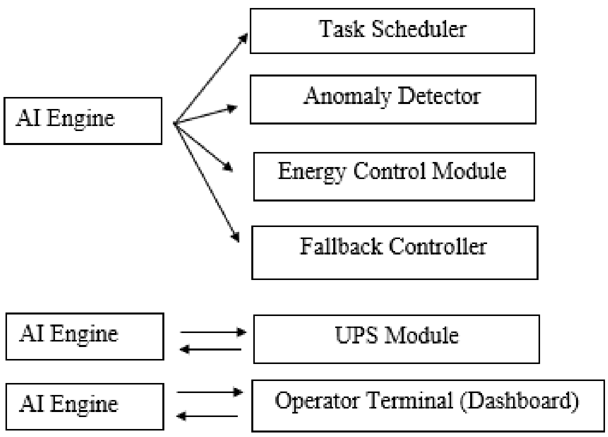

Fig. 3. Architecture of the hardware–software complex and interactions between its main modules

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The combination of these diagrams allows aligning the behavioral logic of the system with its architectural structure, which is essential for further development, testing, and implementation of such systems within the context of digital transformation of construction processes.

Thus, the described UML diagrams make it possible to systematically present the operational logic of the autonomous system, align software and hardware components, and create a foundation for further implementation. It should be noted that UML diagrams are an important stage of system design and may also serve as part of the digital passport of a facility or its digital twin.

The State Diagram in this case represents the dynamic behavior of the autonomous system in response to external events (e.g., power outage, risk detection, loss of communication channel, etc.) and internal conditions (resource-related or operational). This makes it possible to formalize the transitions between operating modes, which is critically important for designing a reliable, fault-tolerant architecture (Figure 4).

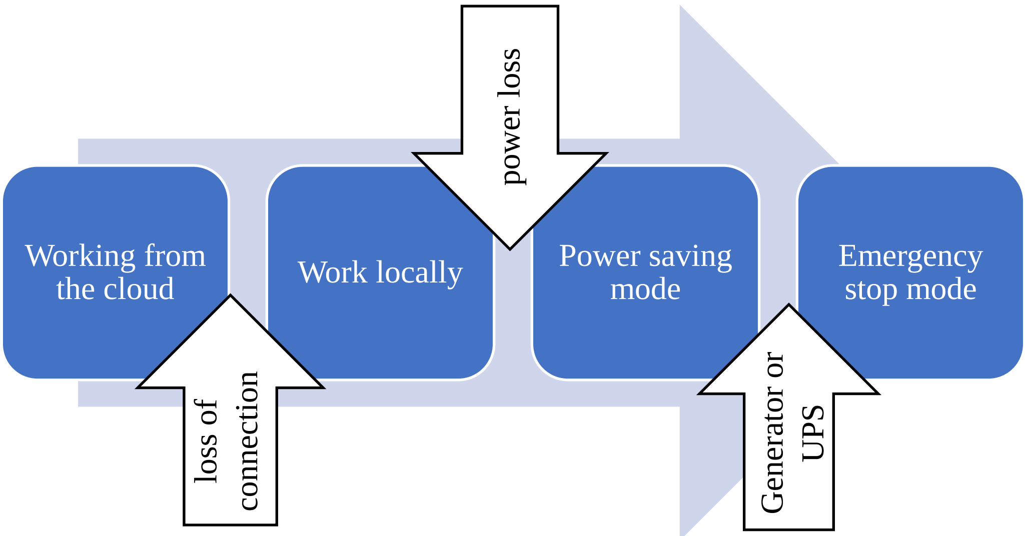

Fig. 4. Mode Switching Model

Based on the state model (Fig. 4), the system operates in several defined modes: normal (standard), autonomous (fallback), and critical (emergency). Switching between these modes is implemented according to event-driven logic and is triggered depending on external or internal factors. Table 4 presents typical scenarios of such transitions.

Table 4 – Typical Scenarios of System Mode Switching

Factor	Trigger	Transition	System Action
Power loss	Voltage drop below critical level, disconnection of the external power source	From “Normal Mode” to “Fallback Mode (powered by UPS/generator)”	Activation of backup power module, reduction of non-priority tasks, activation of the local AI core
Loss of connection with cloud server	No feedback for more than 5 minutes	From “Normal Mode” to “Autonomous Mode without synchronization”	Switch to cached data, local scenario routing through the edge server
Anomaly detection or cyber-attack	Unusual network activity, deviation from behavioral patterns	From “Normal Mode” to “Security/Isolation Mode”	Network isolation, blocking of external APIs, manual confirmation of actions via operator terminal
Restoration of conditions for normal mode	Voltage stabilization, connection recovery, operator confirmation	From “Fallback” or “Security Mode” back to “Normal Mode”	Synchronization of accumulated data with the cloud, activation of optimized schedule

Thus, the combination of the Use Case Diagram and the Component Diagram makes it possible not only to visualize the logic of user interaction with the system and its modular structure but also to gain a deeper understanding of the architectural principles behind the design of the autonomous system. However, to make an informed engineering decision regarding the feasibility of implementing a particular architecture (centralized or modular edge-based), it is necessary to perform a comparative analysis according to the criteria of technical, economic, and functional efficiency.

To justify the choice in favor of a modular architecture, a comparative analysis of centralized and edge-based solutions was conducted according to technical, functional, and economic criteria (Table 5).

Table 5 – Comparison of Centralized and Modular (Edge-based) Architecture

Criterion	Centralized (Cloud-based)	Modular (Edge-based)
Dependency on connectivity	High (internet is critical)	Low (offline operation possible)
Processing speed	Higher with stable network	High in real time (on-site)
Responsiveness	Limited to cloud-defined scenarios	Adaptive, local response
Power consumption	Low on-site, high in the cloud	Medium, depends on hardware
Capital expenditure (CAPEX)	Lower at startup	Higher due to edge infrastructure needs
Security and stability	Vulnerable to network attacks	Local security, fewer vulnerabilities

Based on the above data, it can be concluded that for construction in high-risk environments (e.g., in war zones or critical infrastructure projects), the modular edge-based architecture is more preferable due to its autonomy and reliability. It also provides opportunities for system expansion, including:

- Integration of a local database (PostgreSQL, SQLite) on the edge server for temporary storage of project data.
- Use of a backup GUI interface for management in the form of a minimalist web dashboard.
- Integration with UAVs/drones for automatic aerial monitoring with image processing on an edge video module.

It should be emphasized that the developed architecture of the autonomous intelligent management system does not imply full automation of construction processes by replacing workers with robotic complexes. The focus is primarily on digital coordination and decision-support, not on physical task execution by machines. Human operators remain a key element of the production process, receiving tasks, clarifications, and instructions through integrated digital channels (CDE, mobile applications, site tablets). Such interaction increases productivity and task quality, reduces errors, and optimizes resource use, while maintaining flexibility and accountability of the human factor.

The proposed architecture also incorporates a hybrid fallback mode, where construction professionals continue to play a central role. In this context, it is appropriate to compare it with traditional construction control methods: geodetic surveying, author and technical supervision, preparation and approval of as-built and cost documentation. In conventional practice, these procedures are performed sequentially, often duplicate each other, and require paper-based confirmation and multi-level approvals, which cause delays and risks of data obsolescence.

The autonomous system eliminates these “bottlenecks” through automatic data collection and synchronization in a BIM environment, real-time event logging, and integration with digital cost-estimation and as-built documentation. At the same time, specialists’ capabilities are not diminished but expanded: instead of spending time on routine document verification, they gain tools for rapid data analysis, risk prediction, and decision-making in non-standard situations. Thus, the hybrid system combines automation benefits with expert experience, ensuring reliability and resilience of management even in the event of external threats or digital infrastructure failures.

Conclusions. This paper presents a conceptual architecture of an autonomous intelligent system for managing construction processes capable of ensuring continuity of operation under risks such as power outages, connectivity loss, or cyber-attacks. The necessity of introducing a backup hybrid management system (BHMS) is substantiated, allowing critical technological operations to be performed even if the primary AI system fails.

Three-level system architecture (physical, computational, and communication levels) was developed, with the local edge server as the core element capable of autonomously executing predictive models, controlling equipment, and supporting decision-making logic. To describe the component interaction logic, UML Use Case, Component, and State Diagrams were applied, enabling the formalization of the system's functional structure and mode-switching scenarios.

Comparative analysis of centralized and edge-based architectures demonstrated the advantages of the latter in terms of stability, response speed, security, and independence from infrastructural constraints. Approximate implementation costs for autonomy elements are estimated at 5–10% of the project budget. These costs significantly reduce risks of accidents and downtime while improving construction manageability.

Comprehensive analysis showed that the proposed architecture ensures high adaptability, fast response, and technical independence – features critically important for construction projects under risky conditions. The proposed approach can be applied to projects implemented in unstable environments, such as critical infrastructure facilities, high-risk zones, or strategic infrastructure programs.

Further research on autonomous intelligent construction management systems should focus on several key aspects:

1. Development of mathematical and simulation models to more accurately assess system effectiveness under different external scenarios (from cyber-attacks to energy or material supply disruptions). This will allow verification of system resilience and definition of optimal recovery strategies.

2. Investigation of human–machine interaction, particularly the integration of traditional control functions (geodetic, technical, and author supervision) into the hybrid mode, considering that experts play a key role in confirming and adjusting AI decisions.

3. Expansion of the system architecture through the use of robotic and sensor complexes to automatically collect data from construction sites (e.g., structural geometry monitoring or safety tracking). Defining the optimal level of automation that balances digital infrastructure costs with economic benefits is crucial.

4. Pilot implementation of the proposed system in real construction projects to obtain empirical data on cost reduction, faster response to deviations, and risk mitigation. Such trials would form the basis for developing industry standards and guidelines for implementing autonomous and hybrid management systems in the construction sector of Ukraine.

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АРХІТЕКТУРА АВТОНОМНОЇ ІНТЕЛЕКТУАЛЬНОЇ СИСТЕМИ УПРАВЛІННЯ БУДІВЕЛЬНИМИ ПРОЦЕСАМИ В УМОВАХ РИЗИКУ ЗОВНІШНІХ ВПЛИВІВ

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Анотація. У статті розглянуто проблему забезпечення автономності інтелектуальних систем управління будівельними процесами в умовах ризику зовнішніх впливів, зокрема знеструмлення, втрати зв’язку чи кібератак. Враховуючи зростаючу роль штучного інтелекту (ШІ) у плануванні, моніторингу та керуванні будівельними роботами, авторами поставлено завдання розробити концептуальну архітектуру стійкої до збоїв системи. Метою дослідження є формалізація моделі автономної інтелектуальної системи з резервною логікою керування, здатної зберігати функціональність в умовах критичних збоїв.

Методологія дослідження ґрунтується на системному аналізі архітектурних підходів (централізованої та модульної edge-based), побудові UML-діаграм (use case, component, state), сценарному моделюванні ризиків та техніко-економічному обґрунтуванні впровадження резервної інфраструктури. У статті детально описано трирівневу архітектуру системи, що включає фізичний, обчислювальний та комунікаційний рівні, з центральним елементом – edge-сервером, який виконує ключові функції автономного управління.

Результати дослідження підтвердили ефективність розробленої резервної гібридної системи управління (РГСУ), здатної автоматично реагувати на відмови основного середовища, перемикатися на альтернативні джерела енергії та продовжувати виконання критичних технологічних операцій. Проведено порівняльний аналіз централізованої та edge-based архітектур, розраховано орієнтовне зростання вартості впровадження автономних рішень, що становить 5–10 % від загального кошторису, але значно зменшує ризики зупинок та аварій.

Запропонована модель може бути впроваджена в будівельних підприємствах, що працюють в умовах обмеженого доступу до інфраструктури, а також у проєктах критичної інфраструктури. Подальші дослідження доцільно зосередити на адаптації алгоритмів ШІ до автономного режиму, тестуванні системи в пілотних умовах та стандартизації підходів у галузі інженерного управління будівництвом.

Ключові слова: штучний інтелект, автономна система, edge-computing, управління будівництвом, відмовостійкість, архітектура програмного забезпечення, UML-діаграми, резервне керування, критична інфраструктура.

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IMPROVEMENT OF COLD CONCRETE JOINTS USING WET GRINDING METHOD

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Abstract. The article considers the process of cold joints formation that arise as a result of interruptions during the placement of concrete mix and can significantly affect the subsequent mechanical behavior of concrete and reinforced concrete structures. The characteristic defects that are formed both at the manufacturing stage and during the operation of structural elements, as well as their impact on durability and load-bearing capacity, are analyzed in detail. Special attention is paid to modern methods and materials used for the repair and restoration of damaged concrete elements, in particular, special repair mixtures, modified cements, chemical additives and approaches to base preparation. One of the key methods considered in the work is the technology of wet shotcrete, which allows for effective restoration of damaged areas and ensuring high-quality adhesion between old and new concrete. The features of regulating the technical properties of repair mixtures by using optimal compositions, selection of aggregates, modification of the mixture and control of hardening conditions are presented. The importance of proper surface preparation of existing concrete is emphasized, which largely determines the quality of the contact zone.

The study is aimed at determining the optimal parameters for applying repair materials by shotcrete. In laboratory conditions, partial application of a 1 cm thick layer of repair mixture was used using a compact test rig. A method for determining the tensile strength of fine-grained concrete during bending was developed using standardized forms modernized with special partitions. Prepared halves of beams with surface angles of 90°, 45° and 22.5° to the horizontal were used as elements of "old concrete". Such a design solution allowed to increase the contact area, minimize flow turbulence during spraying and assess the influence of the spatial position of the cold joint.

Within the framework of the study, a two-factor nine-point experimental design was formed, in which the angle of the cold joint plane (90°, 45°, 22.5°) and the speed of spraying the shotcrete-fiber concrete mixture (0 m/s, 35 m/s, 70 m/s) were varied. A set of experimental tests was carried out, the results of which are presented and analyzed in the work, which allowed us to establish the regularities of changes in the strength and nature of the fracture of the repaired samples.

Keywords: cold joint concreting, wet shotcrete method, repair work, partial shotcrete, experimental planning.

Introduction. The characteristics of the concrete structures depends largely on the integrity of the material throughout its volume. Sometimes, due to interruptions or delays in the concreting procedure, when the second batch of concrete is not poured immediately after the first one, cold joints occur [1-4]. In such situations, surface of weakness is created in the concrete element body, which can result in the structural problems in the final concrete structure [5].

Monolithic concreting is usually performed floor by floor, and delay in the concrete mix inevitably creates the potential for cold joints to form at column-slab and column-beam joints. Large foundation elements may require segmented concreting due to time constraints, creating parts prone to cold joints. Their location and dimensions should generally be determined by the type of structure in order to guarantee its functionality and aesthetic appearance [6].

Analysis of recent research and publications. The previous studies have mainly focused on the general effect of cold joints on concrete properties such as compressive strength, tensile strength and durability. However, the specific effect of cold joint arrangement on the bending behavior of concrete elements has not been thoroughly investigated. The ability of the system to withstand the maximum force depends on factors such as the location of the cold joint, the pouring interval and the relationship between the location of the cold joint and the direction of the applied forces [7].

The regulatory documents state that concrete mixtures are recommended to be arranged in structures that are concreted in horizontal layers of the same thickness without gaps with a consistent direction of laying in one direction in all layers. The surface of the construction joints arranged when laying the concrete mixture with interruptions should be perpendicular to the axis of the columns and beams, the surface of the slabs and walls that are being concreted. Re-concreting is allowed to be performed after the concrete reaches a strength of at least 1.5 MPa [8, 9].

In order to prevent the formation of cold joints and excessive settlement or overloading of the mould and its supporting structures, it is necessary to choose an appropriate speed for placing and compacting the concrete mix. During molding, a cold joint may form if the concrete mix hardens before the subsequent layer of concrete mix is placed and compacted. Special attention should be paid to the areas where previously placed concrete mix has not been compacted before placing the subsequent layer [10].

Before concreting, the location of the construction joints should be carefully considered and their position agreed. They should usually be located at right angles to the direction of the element. If special preparation of the joint surfaces is required, this should be indicated [8-10].

Partial shotcrete is applied to arrange cold joints using a shotcrete gun. With this method, a thin layer of shotcrete is applied for further concreting [11].

By analyzing the impact of cold joints and their control in different elements and at different angles, the study provides valuable information for construction, contractors and workers on the construction site in order to optimize construction protocols during large-scale concreting.

The purpose of the study presented in the paper is to determine the analytical dependences of the tensile strength index during bending of repair mixtures applied by wet shotcrete technology with a compact installation when arranging cold joints.

The objectives of the study are to analyze modern methods and materials applied for the repair of concrete and reinforced concrete elements of building structures and structures, including for the control of cold joints. To investigate the fracture of cold joints specimens placed at an angle.

Materials and study methods. When repairing with cement mortars and concrete, depending on specific conditions, special requirements are imposed on them: acceleration of the hardening rate, slowing down the setting process, the possibility of thinning the concrete mixture, no shrinkage or expansion, high density, chemical resistance and adhesion to "old" concrete. Regulation of the technical properties of concrete is achieved by applying special types of cement, additives and aggregates, special laying methods and hardening conditions, as well as appropriate preparation of the surface of old concrete [12, 13].

Partial application of shotcrete by wet method was carried out by a compact shotcrete installation (Fig. 1), which operates with compressed air from a mobile compressor station of appropriate capacity. The low-power operation of the compact installation can be effectively used for the installation and repair of thin-walled reinforced concrete elements of buildings. The bunker gun (hopper) is designed according to the principle of a compressor nozzle and has a bunker volume of 6 dm^3. With a coating thickness of 10 mm, in two layers, the gun’s performance is about 10 m^2/h.

Compared to the dry method, the wet shotcrete method requires more work at the beginning (preparation and feeding the mixture into the pump) and at the end (cleaning the equipment). In addition, the wet shotcrete method has a limited time of use of the prepared mixture, and if the concrete mixture is not applied during this time, the mixture cannot be used.

The composition of the mixture for the wet shotcrete method contains: cement, inert materials, additives (superplasticizers), liquid, fibers (dispersed reinforcement). The same requirements are imposed on shotcrete-concrete mixtures in construction as on conventional concrete mixtures.

Fig. 1. Compact shotcrete installation:
1 – hopper; 2 – compressor; 3 – hose

It is much more difficult to achieve all of the above-mentioned requirements with wet shotcrete, especially on open construction sites. Previously, this was completely impractical, but today it is possible to approach the ideal composition of the mixture by means of special additives. A very important criterion for shotcrete mixtures is the number of small particles that make up the bulk of the composition, and the strength characteristics.

The concrete bases have high absorption and absorb most of the moisture from the repair mixture. To prevent the repair mixture from peeling off in the first year, a penetrating primer should be applied. For example, consider the use of Knauf Betokontakt as a preparation for high-quality finishing of concrete and foam concrete surfaces. The mortar does not penetrate deeply into the base and in most cases penetrates the surface at a level of 4-5 mm. However, the main advantage of this composition is that it creates high adhesion on porous surfaces. As soon as the liquid dries, a rough layer is formed, finishing materials adhere perfectly [14].

For an experiment to determine the tensile strength of fine-grained concrete during bending of the repair mixture. To check the adhesion of fine-grained shotcrete, a mold for beam samples 4×4×16 cm and finished half-samples in the form of old concrete with age of 1 day was used. This mold is most suitable for creating samples of fine-grained shotcrete for preliminary experiments. The ends of the finished halves were made at angles of 90° – according to the requirements of regulatory documents, 45° – average value, and 22.5° – similar to the natural angle of spreading of the concrete mixture, degrees with a change in the behavior of the air flow in the shotcrete technology and a change in the contact area (Fig. 2).

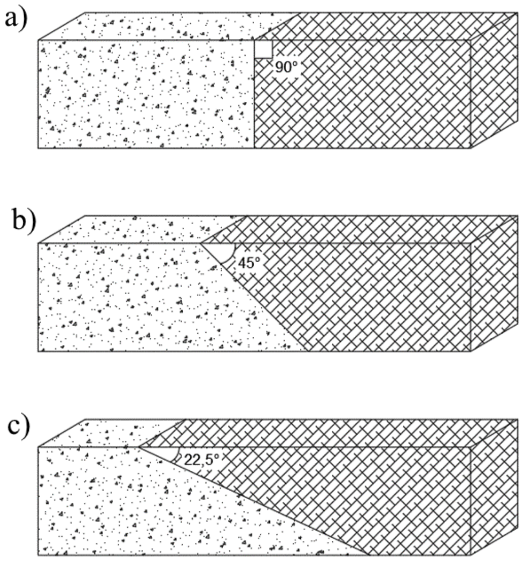

Fig. 2. Location of cold joints of beam samples:
a – 90°; b – 45°; c – 22.5°

Study results. The shortened experimental design with accepted factors was selected and ranges of variation of the parameters of the fine-grained shotcrete layer thickness are summarized in Table 1 [15, 16]. The study assumed changing the angles of the surface of the cold joints from 90° to 22.5° for the sanmples of the previous concreting layer, while the speed of the mixture supply varied from 0 to 70 m/s.

Table 1 – Experimental plan and parameter levels

No.	Normalzed values of factors		Natural values of factors	
	x_1	x_2	X_1	X_2
			Angle, °	Speed, m/s
1	-1	-1	90	0
2	-1	0	90	35
3	-1	1	90	70
4	0	-1	45	0
5	0	0	45	35
6	0	1	45	70
7	1	-1	22.5	0
8	1	0	22.5	35
9	1	1	22.5	70

The BauGut plasticizer was applied as a modifier. Due to this agent, it became possible to significantly increase the concrete mixture plasticity without the need to change the water-cement ratio, i.e. without increasing the water content, which facilitates the formation of a layer of fine-grained concrete during application.

To improve the physical characteristics of the material, basalt fiber was included in the composition of the fine-grained shotcrete mixture. To ensure the correct operation of the shotcrete installation with a bunker gun with a diameter of 9 mm, basalt fibers were crushed to a length of 3–4 mm.

The test samples were manufactured in standard molds intended for the formation of the beams made of fine-grained concrete measuring 40×40×160 mm (Fig. 3). The characteristics of the molds for the manufacture of such beams were as follows: type – beam mold (BM); number of samples – 3; width – 40 mm; length – 160 mm; height – 40 mm [15, 16].

Fig. 3. Partial shotcreting of the sample surfaces of the previous layer of concreting in a standard mold

The modified inserts were applied in order to prevent manufacturing defects in the lower corners caused by compressed air vortices during shotcreting. Following generally accepted practice for placing concrete, cement milk from the cold joint surface was removed in 24 hours, partially shotcreted and poured with the next layer of concrete.

In order to so simulate the conditions of monolithic structure concreting interruption, samples in the form of half-beams measuring 4×4×16 cm were applied as a base, one end of which was inclined at an angle of 90° to 22.5° relative to the horizontal. Additionally, this form was modified using insertable perforated partitions, which allowed the manufacture of shotcrete samples in a laboratory environment, taking into account the characteristics of the mobile equipment used for applying the mixture.

The samples were tested using MI-100 equipment, which is designed to determine the tensile strength of samples with a size of 40×40×160 mm i.e., which were manufactured in beam forms. The load is transmitted to the center of the beam, so the cold joint was located in the central part. The force acting on the beam is directed vertically, so the joint was located in the horizontal plane so that it contributes to the greatest loads. The adhesion of the sample cold joint at an angle of 45° withstands the forces that arise during destruction (Fig. 4). The plane of the beam section passes through the center and through the material of the previous and subsequent layers of concreting.

Fig. 4. Sample failure relative to the location of beam cold joints

Conclusion and further study prospects:

1. The preparation of the surface of previous concrete layer and the application of primers described in the paper contribute to improving adhesion when arranging cold joints.

2. The cold joints arranged according to the technology and placed at an angle withstand the load, and the destruction of the samples occurs in a different plane.

3. A compact installation for wet fine-grained shotcrete can be applied to arrange cold joints that arise during monolithic concreting.

4. A promising direction of study is partial shotcreting with a compact installation when arranging cold joints in heavy concrete.

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УЛАШТУВАННЯ ХОЛОДНИХ ШВІВ БЕТОНУ МЕТОДОМ МОКРОГО ТОРКРЕТУВАННЯ

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Анотація. У статті розглянуто процес утворення холодних швів, що виникають унаслідок перерв під час укладання бетонної суміші та здатні суттєво впливати на подальшу механічну поведінку бетонних і залізобетонних конструкцій. Детально проаналізовано характерні дефекти, які формуються як на стадії виготовлення, так і під час експлуатації елементів конструкцій, а також їхній вплив на довговічність та несучу здатність. Окрему увагу приділено сучасним методам та матеріалам, що застосовуються для ремонту й відновлення пошкоджених бетонних елементів, зокрема спеціальним ремонтним сумішам, модифікованим цементам, хімічним добавкам та підходам до підготовки основи.

Одним з ключових методів, розглянутих у роботі, є технологія мокрого способу торкретування, яка дозволяє ефективно відновлювати пошкоджені зони та забезпечувати якісне зчеплення між старим і новим бетоном. Наведено особливості регулювання технічних властивостей ремонтних сумішей шляхом використання оптимальних складів, підбору заповнювачів, модифікування суміші та контролю умов твердіння. Підкреслено важливість належної підготовки поверхні існуючого бетону, що значною мірою визначає якість контактної зони.

Дослідження спрямоване на визначення оптимальних параметрів нанесення ремонтних матеріалів методом торкретування. У лабораторних умовах використовувалося часткове нанесення шару ремонтної суміші товщиною 1 см за допомогою компактної випробувальної установки. Розроблено методику визначення міцності на розтяг при вигині дрібнозернистого бетону із застосуванням стандартизованих форм, модернізованих спеціальними перегородками. Як елементи «старого бетону» використовувались підготовлені половинки балочок із кутами поверхні 90°, 45° та 22,5° до горизонталі. Таке конструктивне рішення дозволило збільшити площу контакту, мінімізувати турбулентність потоку при набризку та оцінити вплив просторового положення холодного шва.

У межах дослідження сформовано двофакторний дев’ятиточковий план експерименту, у якому варіювалися кут розташування площини холодного шва (90°, 45°, 22,5°) та швидкість набризку торкретфібробетонної суміші (0 м/с, 35 м/с, 70 м/с). Проведено комплекс експериментальних випробувань, результати яких наведені та проаналізовані в роботі, що дозволило встановити закономірності зміни міцності та характеру руйнування ремонтованих зразків.

Ключові слова: холодні шви бетонування, мокрий спосіб торкретування, ремонтні роботи, часткове торкретування, планування експерименту.

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ВИМОГИ ДО ОФОРМЛЕННЯ СТАТЕЙ
у збірнику наукових праць
“Сучасне будівництво та архітектура”

До опублікування у фаховій збірці наукових праць приймаються раніше не опубліковані наукові статті, із зазначеною нижче **тематикою публікацій**:

1. Архітектура.
2. Будівельні конструкції.
3. Будівельні матеріали та технології.
4. Гідротехнічне та транспортне будівництво.
5. Інженерні мережі та обладнання.
6. Основи та фундаменти.
7. Технологія та організація будівельного виробництва.

Стаття повинна відповідати тематиці збірника, публікуватися вперше і включати такі елементи:

• актуальність та постановку проблеми у загальному вигляді, її зв'язок із важливими науковими чи практичними завданнями;
• аналіз останніх досліджень і публікацій, у яких представлено вирішення даної проблеми і на які спирається автор; виділення невирішених раніше частин загальної проблеми, яким присвячується дана стаття;
• формулювання мети статті (постановка завдання);
• виклад основного матеріалу дослідження з повним обґрунтуванням отриманих наукових результатів;
• висновки з даного дослідження і перспективи подальшого розвитку у даному напрямку;
• список літератури.

Загальні вимоги до оформлення тексту

Статті подаються в електронному вигляді файлом Word 97 − 2003 в форматі .doc. Назва файлу має містити номер тематики публікації та прізвище першого автора (наприклад, 5 Іванов.doc).

Статті подаються українською чи англійською мовою і друкуються мовою оригіналу.

Текстова частина статті набирається на аркушах формату **А4** шрифтом **Times New Roman 12 пт** через одинарний інтервал, вирівнюється по ширині сторінки, поля по 2 см з усіх боків, абзацний відступ − 1,0 см. **Обсяг статті 7-16 повних сторінок разом з анотаціями.**

Структура статті:

− ***індекс УДК*** (вирівняно по лівому краю без абзацного відступу, прописний, напівжирний);
− ***назва статті*** (відцентрована, усі літери прописні, напівжирні, переноси не допускаються);
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Текст першої анотації пишеться мовою основного тексту статті та повинен бути **не менш як 1800 знаків**.

Текст другої анотації, якщо видання не є повністю англомовним, кожна публікація не англійською мовою супроводжується анотацією англійською мовою обсягом **не менш як 1800 знаків**. Якщо видання не є повністю україномовним, кожна публікація не українською мовою супроводжується анотацією українською мовою обсягом **не менш як 1800 знаків**. Друга анотація розміщується в кінці статті після списку літератури на англійській мові.

Дві анотації повинні коротко повторювати структуру статті, що включає вступ, мету, методику, результати, висновок. Машинний переклад **не дозволяється.**

− ***ключові слова*** (міжрядковий інтервал не робиться, абзацний відступ, назва напівжирна, текст ключових слів не більше 6–8 слів).

Назва статі, прізвище і ініціали, науковий ступінь, вчене звання, місце роботи, анотація і ключові слова – повторюються українською та англійською мовами.

Між рядками з індексом УДК, назвою статі, прізвищем авторів, анотацією, основним текстом і переліком літератури, літературою на англійській мові та другою анотацією одинарний інтервал.

− ***Основний текст статті.***

Структура основного тексту статті згідно з постановою ВАК України № 7-05/1 від 15.01.2003 р. (Бюлетень ВАК України №1, 2003 р.) повинна мати такі необхідні елементи (***назви структурних елементів в тексті статті потрібно виділити напівжирно*)**:

– вступ (постановка проблеми у загальному вигляді та її зв’язок з важливими науковими чи практичними завданнями);

− аналіз останніх джерел досліджень і публікацій, у яких започатковано розв’язання проблеми (бажано, щоб це був аналіз останніх публікацій у фахових журналах) і на які опирається автор, виділення не розв'язаних раніше частин загальної проблеми, яким присвячується стаття;

– постановка мети та завдання (формулювання мети та завдань досліджень);

– матеріали та методи дослідження (опис використаних матеріалів та методів дослідження проблеми, що розглядається у статті);

– основний матеріал і результати (виклад основного матеріалу дослідження з повним обґрунтуванням отриманих наукових результатів);

− висновки (наукова новизна, наукове та практичне значення результатів дослідження, перспективи подальших наукових розроблень);

− ***література*** (відцентрована, напівжирна; посилання в тексті подають у квадратних дужках [2]; список літератури наводиться відповідно порядку посилань у тексті згідно з ДСТУ 8302:2015 та записується в стовпчик; написання «Джерела інформації», «Перелік літератури» **не допускається**). Бібліографічний список наводиться мовою оригіналу та транслітерується. Кількість посилань на літературні джерела у статті повинно бути не менше 15 джерел. Особлива увага приділяється сучасним англомовним статтям, зокрема індексованих WoS або Scopus.

− ***бібліографічний список (References).*** Для відтворення українських власних назв засобами англійської мови при перекладі публікації англійською мовою застосовується транслітерація. Найменування організацій та установ, що не перекладаються на англійську мову, також транслітеруються. Транслітерація прізвищ авторів виконується залежно від мови оригіналу джерела відповідно до вимог Постанови Кабінету Міністрів України від 27.01.2010 р. № 55 «Про впорядкування транслітерації українського алфавіту латиницею». Бібліографічний список повинен бути оформлений з використанням стиля ***IEEE STYLE*** згідно з «Міжнародним стилем цитування та посилання в наукових роботах», Київ, 2016.

Таблиці слід виконувати в редакторах Word без заливання. Кожна таблиця має бути надрукована з відповідним заголовком та нумерацією після першого посилання на неї.

Ширина таблиць не повинна перевищувати поля сторінки. Шрифт в таблиці повинен відповідати шрифту статті.

Формули мають бути виконані в редакторі формул *Equation 3.0* чи *MathType* з використанням тільки загальноприйнятих шрифтів (Times New Roman; Symbol). Кожна формула набирається як один об'єкт, нумерація формул арабськими цифрами справа в дужках вирівняна по ширині сторінки.

Рисунки (діаграми, фото), подаються у чорно-білому, кольоровому варіанті або у градаціях сірого кольору після першого посилання на них; мають бути згруповані та являти собою один графічний об'єкт; мати нумерацію та підпис позначення ось координат. Розміри підписів на рисунку повинні відповідати шрифту Times New Roman 12 пт.

Разом зі статтею подаються:

− відомості про автора (авторська довідка): прізвище, ім'я, по батькові (повністю); вчене звання, вчений ступінь; посада, місце роботи; контактні адреси й телефони; поштова адреса, на яку надсилати примірник збірника

– рецензія на статтю, якщо автором є аспірант без співавторів з вченим ступенем та вченим званням.

Статті, які не відповідають наведеним вимогам, до розгляду не приймаються.

Подані матеріали підлягають додатковому рецензуванню членами редколегії або провідними фахівцями за науковими напрямами, тому можуть бути повернені авторам на доопрацювання.

Остаточне рішення щодо публікації статті приймає редакційна колегія видання.

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