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АРХИТЕКТУРА

СТРОИТЕЛЬСТВО

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REVIEW ARTICLE

MODERN MOSQUE ARCHITECTURE: A BALANCE BETWEEN GLOBALIZATION AND A SENSE OF REGIONAL IDENTITY

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Abstract. *Modern trends of the time require significant changes in the spatial planning, functional and artistic-image design of architectural objects, including religious buildings as mosques. With the changing pace of life characteristic of the era of globalization and the growing level of religious involvement in society, there is a need for new architectural trends. These changes concern both the functional and technological aspects as well as the visual characteristics of buildings, including mosques, which must meet the requirements of modernity. This fact implies the creation of architecture that can meet the needs of the religious community, ensure inclusiveness, sustainability and conformity with modern technological and cultural expectations of society. In modern conditions, mosques, as places of worship designed for religious practices, must now become architectural objects that reflect the dynamics of social, cultural and technological transformations. Our research focuses on the study of examples of architectural solutions of modern mosques in the world and Kazakhstan, which successfully combine innovation and tradition. We analyze architectural and artistic techniques, stylistic trends and ways of adapting the form of Islamic architecture buildings and their canonical components in accordance with the needs of modern society. This study will identify key trends in the integration of traditional architectural elements characteristic of different regions with innovative solutions. This will help to substantiate the challenges of achieving a balance between traditional architectural forms and modern technologies in the context of global changes in architecture and technological progress.*

Keywords: *mosque architecture, regional architecture, religious architecture, regional identity*

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ҒЫЛЫМИ МАҚАЛА

МЕШІТТЕРДІҢ ЗАМАНАУИ СӘУЛЕТІ: ЖАҺАНДАНУ МЕН АЙМАҚТЫҚ СӘЙКЕСТІКТІ ІЗДЕУ АРАСЫНДАҒЫ ТЕПЕ-ТЕҢДІК

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Аңдатпа. *Қазіргі заманның үрдістері сәулет нысандарының, соның ішінде мешіттер сияқты культтік архитектураны да қоса алғанда, кеңістіктік-жоспарлау, функционалдық және көркем-образдық шешімдеріне елеулі өзгерістер енгізуді талап етеді. Ғаламдану дәуіріне тән өмір ырғағының өзгеруі және қоғамда діни қатысудың артуы жаңа сәулеттік үрдістерге деген қажеттілікті тудырып отыр. Бұл өзгерістер функционалдық және технологиялық аспектілермен қатар, мешіттерді қоса алғанда, ғимараттардың визуалды сипаттамаларын да қамтиды, олар қазіргі заман талаптарына сай болуы тиіс. Бұл жағдай діни қауымдастықтың қажеттіліктерін қанағаттандыра алатын, инклюзивтілікті, орнықтылықты қамтамасыз ететін және қоғамның қазіргі технологиялық әрі мәдени үміттеріне сай келетін сәулет үлгісін қалыптастыруды көздейді. Қазіргі жағдайда мешіттер діни рәсімдер мен ғұрыптарды орындауға арналған культтік құрылымдар ретінде енді социомәдени және технологиялық трансформациялардың серпінін бейнелейтін сәулеттік нысандарға айналуы қажет. Біздің зерттеуіміз қазіргі заманғы мешіттердің инновациялар мен дәстүрлерді сәтті ұштастырған архитектуралық шешімдерінің әлемдегі және Қазақстандағы мысалдарын зерттеуге, архитектуралық-көркемдік тәсілдерді, стильдік бағыттарды талдауға және ислам сәулетінің ғимарат пішіндерін қазіргі қоғамның қажеттіліктеріне сай бейімдеу жолдары мен оның канондық құрамдас бөліктерін қарастыруға бағытталған. Бұл зерттеу түрлі өңірлерге тән дәстүрлі сәулеттік элементтерді инновациялық шешімдермен біріктірудегі негізгі үрдістерді анықтауға мүмкіндік береді. Бұл дәстүрлі сәулет формалары мен заманауи технологиялар арасындағы тепе-теңдікті сақтауға бағытталған міндеттерді негіздеуге жол ашады, әсіресе архитектура мен технология саласындағы жаһандық өзгерістер жағдайында.*

Түйін сөздер: *мешіт сәулеті, аймақтық сәулет, культтік сәулет, аймақтық сәйкестік*

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НАУЧНАЯ СТАТЬЯ

СОВРЕМЕННАЯ АРХИТЕКТУРА МЕЧЕТЕЙ: БАЛАНС МЕЖДУ ГЛОБАЛИЗАЦИЕЙ И ПОИСКОМ РЕГИОНАЛЬНОЙ ИДЕНТИЧНОСТИ

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Аннотация. *Современные веяния времени требуют значительных изменений в объёмно-планировочном, функциональном и художественно-образном решении архитектурных объектов, включая культовую архитектуру как мечети. В условиях изменения темпа жизни, характерного для эпохи глобализации, и растущего уровня религиозной вовлечённости в обществе возникает потребность в новых архитектурных тенденциях. Эти перемены касаются как функциональных и технологических аспектов, так и визуальных характеристик зданий, включая мечети, которые должны отвечать требованиям современности. Данный факт предполагает создание архитектуры, способной удовлетворить потребности религиозного сообщества, обеспечить инклюзивность, устойчивость и соответствие современным технологическим и культурным ожиданиям общества. В современных условиях мечети, как культовые сооружения, предназначенные для отправления религиозных обрядов и ритуалов, должны теперь стать архитектурными объектами, отражающими динамику социокультурных и технологических трансформаций. Наше исследование фокусируются на исследовании примеров архитектурных решений современных мечетей в мире и Казахстане, которые успешно сочетают инновации и традиции, анализе архитектурно-художественных приёмов, стилистических направлений и путей адаптации формы зданий исламской архитектуры и их канонические составляющие в соответствии с потребностями современного общества. Данное исследование позволит выявить ключевые тенденции в интеграции традиционных архитектурных элементов, характерных для различных регионов, с инновационными решениями. Это позволит обосновать задачи достижения баланса между традиционными архитектурными формами и современными технологиями в условиях глобальных изменений в архитектуре и технологического прогресса.*

Ключевые слова: *архитектура мечети, региональная архитектура, культовая архитектура, региональная идентичность*

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CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

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Зерттеу Қазақстан Республикасы Ғылым және жоғары білім министрлігі Ғылым комитетінің IRN AP19680138 "Жаһандану жағдайында тәуелсіз Қазақстан сәулетінің тұрақты дамуының факторы ретінде аймақтық бірегейлік" гранттық қаржыландыру шеңберінде жүргізілді.

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БЛАГОДАРНОСТИ / ИСТОЧНИК ФИНАНСИРОВАНИЯ

Исследование проводилось в рамках грантового финансирования Комитета науки Министерства науки и высшего образования Республики Казахстан IRN AP19680138 “Региональная идентичность как фактор устойчивого развития архитектуры независимого Казахстана в условиях глобализации”.

КОНФЛИКТ ИНТЕРЕСОВ

Авторы заявляют, что конфликта интересов нет.

1 INTRODUCTION

One of the most significant and relevant studies in modern architecture is the exploration and preservation of regional identity. This study is influenced by the globalization process and its challenges. The evolution of design strategies for modern mosques is taking place with these challenges in mind. These challenges include: the need to unify architectural styles while preserving local traditions, the impact of urbanization on space in the built environment, the importance of environmental sustainability, and the need for technological innovation and inclusivity in design.

The incorporation of new approaches and innovative technologies contributes to a comfortable, ecologically orientated architectural environment, while the strengthening of the regional component in modern mosque architecture contributes to the preservation of cultural content and the designation of local belonging.

It is worth noting that regional identity in architecture is not affixed style or image, but a dynamic system based on an informed understanding of local traditions and the essential nature of architecture within a specific location, as expressed through the unique vision of a local architect **(Abdrassilova & Murzagaliyeva, 2020, Danibekova, 2023)**.

A mosque is a stable type of religious building characterised by the presence of a number of canonical architectural forms, a characteristic functional zoning and a set of rooms. As it happened, these canons have always been preserved as unchanged as possible in Islamic cult architecture in different regional conditions. Islamic architecture is based on three key elements of the spatial planning of mosques. These are the minaret, mihrab and minbar, which are integral components of the religious space, ensuring its functionality and image recognizability.

The architectural typology of public buildings and structures, adapted to modern trends, develops basic principles of object formation based on their characteristic features, visual signs, and functional content that correspond to the needs of modern society. This approach is emphasized in the textbook "Architectural Typology of Buildings and Structures," which systematizes and elaborates on principles for the development of building types that take into account their desired features and characteristics **(Zmeul & Makhanko, 2005)**.

In the context of global architectural trends and with the increasing interest in the dynamics of mosque architecture, modern architects are now in search of new approaches to the aesthetics of shaping religious buildings. Atypical architectural methods are required, which, within the framework of religious canons and traditional principles of Islamic architecture, will allow adapting mosques to the changing demands of society.

Modern architects are demonstrating radically new approaches to mosque design that differ significantly from traditional solutions. This has led to a transformation of the traditional aesthetic image of these sacred buildings. The changes are not only seen in the planning structure but also in the functional range of mosques, which has expanded to meet the needs of today's Muslim society. Architects are also proposing unconventional silhouettes and shapes for mosques that go beyond the typical visual characteristics associated with these religious structures.

According to modern scholars, the architectural designs of mosques are subject to change, transformation and adaptation to modern circumstances. Even elements that seem to be inviolate, such as the mihrab and minaret, are being reconsidered: some contemporary architects from Muslim-majority countries suggest that it is feasible to do away with these traditional features **(Muksinov & Babajanova, 2005, Shukurov, 2014, Syahid, 2018)**. In the search for a solution to the challenge of achieving the uniqueness of mosque architecture, a balanced approach appears to be the most promising. This approach is based on a harmonious combination of progressive architectural innovation, local natural and climatic factors, cultural traditions, and Islamic

architectural principles. This method has the potential to create a new paradigm in mosque architecture that balances global trends with a recognition of regional identity, while maintaining their functional and spiritual importance.

2 LITERATURE REVIEW

The scientific literature devoted to the study of mosque architecture has a wide range. The canonical requirements for buildings and forms of mosques, their functional zoning, as well as the evolution of architectural elements are considered in the studies of Frishman M., Khan H., Grabar O., Necipoglu G. **(Frishman & Khan, 1994, Grabar, 1978, Necipoglu, 1998)**.

The evolution of mosque architecture in the territory of Kazakhstan is studied: from simple rectangular forms of the 9th-10th centuries, oriented on functionality, to more complex constructions of the 11th-16th centuries with domes and minarets. The increase in the number of mosques, their forms and elements were due to the growing influence of Islam and partial integration of local architectural traditions. This issue was studied by prominent Kazakh scientist B. Glaudinov **(Glaudinov, 1999, Glaudinov, 2019, Kasymbekova & Glaudinov, 2012)**. The research noted that during the 9th and 10th centuries, mosques in Kazakhstan were simple structures with rectangular rooms. However, from the 11th to 16th centuries, more complex shapes such as domes and minarets began to be used as important elements in mosque architecture.

The scientists have revealed the connection of local traditional features of Islamic religious buildings with Persian and Ottoman architectural styles, characterized by the use of domed structures, arched vaults, calligraphic and ornamental decorations. The problem of loss of unique regional features of cult architecture in the conditions of globalization is considered in detail **(Galimzhanova & Glaudinova, 2011, Sadykova Sh., 2018, Beisenova & Samoilov, 2022, Slieptsov et al., 2024)**. The focus of our research is on works containing studies of contemporary trends in the development of mosque architecture in the 21st century with examples of reinterpretation of their canonical forms and elements **(Kisamedin, 2013, Shukurov, 2014, Shanbayeva, Kantarbayeva & Mahoney, 2024, Putra et al., 2025, Mertyurek & Demirbas, 2023, Tamimi & Pankina, 2024)**.

3 MATERIALS AND METHODS

When cultural and architectural traditions are influenced by globalization and unification is observed, it is important to find a balance between preservation of local specificity and adaptation to modern requirements. Formation of architectural and spatial design of religious buildings and their functions should be based on the context of the local environment with the integration of domestic traditional elements. This should be done by considering climatic, cultural, historical, socio-political, and economic factors in order to create a harmonious and appropriate design. This requires the exploration of alternative design approaches that ensure a harmonious combination of tradition and innovation within the modern architectural discourse.

The research is based on a comprehensive approach to understanding the balance between global trends and local identity in modern mosque architecture. This includes a review of academic literature, architectural projects, and periodicals, as well as an analysis of the architectural and artistic techniques and stylistic trends used in mosque design. The goal is to identify conceptual approaches and trends in the architectural and planning solutions used in various regions around the world.

We also aim to identify patterns of regional development in mosque architecture, considering the influence of climatic, socio-cultural, and economic factors. This is done by examining spatial regional archetypes and their evolution through the principle of continuity, while also taking into account modern interpretations.

In the works of contemporary architects, the concept of the exterior design, functional zoning, and interior space in modern religious buildings challenges established design stereotypes. In the

21st century has brought the realization that the invocation of the Creator (namaz) is the most important part of Islam, and that canonical elements such as the dome, minaret, mihrab, etc. are not directly related to the act of prayer itself. The fact that a Muslim needs only a small space oriented towards Mecca for worship freed architects from being rigidly bound to the canonical forms of the mosque, opening the way to a more free and flexible architectural approach.

By referring to the Quran, the sacred book of Islam, which does not provide specific instructions on mosque architecture, modern architects are able to create contemporary interpretations of religious structures **(Wiebe, 2012)**. This led to a reconsideration of the architectural form of mosques, with the focus on creating a space that was in line with their spiritual function and open to architectural innovation, rather than simply following traditional elements.

4 RESULTS AND DISCUSSIONS

We have considered examples that demonstrate the possibility of creating a prayer space without traditional domes and minarets. These examples focus on the search for regional identity and take into account the local context.

Figure 1 shows the Masjid Al Irsyad Mosque (Bandung, Indonesia, 2010, architect Ridwan Kamil), a giant parallelepiped structure with a transparent mihrab surrounded by a water tank. Here, the open mihrab with views of nature is the compositional focal point of the entire structure, which is completely atypical for the historically established image of a religious building. However, the author considered that ‘a mosque is a place where Allah is worshipped...the shape of which depends on human imagination and is not mentioned in the Qoran...and the dome does not signify Islam...’. Thus, the dome as a canonical element of Islamic architecture was excluded from the general concept of the building **(Indonesia's unique mosques, 2019)**.

The architect explained the decision to reject the use of a dome due to the specific local conditions of the tropical climate. Dome and vaulted roof structures are traditionally used in hot and dry regions of Central Asia, the Middle East, and the Near East as a means of protecting buildings from excessive solar radiation by cooling the air inside the dome space **(Murzagaliyeva & Abdrassilova, 2018)**. R. Kamil selected the methods of constructing the building that are appropriate for the conditions of the tropical climate, imbuing the structure with regional characteristics. Some of the concrete blocks in the walls are hollow, providing natural ventilation and daylighting for the interior of the mosque during the day.

The Assiaf Mosque (Singapore, Forum Architects) is an interesting example of a conscious deviation from established forms of Islamic architecture in favor of a modern, functional and culturally sensitive approach. The context of the city-state of Singapore is multinational and multicultural. The architects refused to use elements characteristic of Muslim architecture and formed a neutral architectural image devoid of strong ethno-confessional associations. Thus, the project is characterized by pronounced local features: inclusiveness, universality. Along with the desire for adaptability of architecture in the conditions of a global metropolis, the regional character of the building is manifested in the consideration of local specific climatic conditions - high humidity and tropical air temperature. Under these circumstances, the mosque project focuses on reducing the number of enclosed spaces. Instead of traditional walls, open-work aluminum screens with Arabic patterns are used, providing effective natural ventilation and lighting while simultaneously creating a visual effect of lightness and partial "de-materialization" of the facade, enhancing the building's connection to the environment.

In the course of studying modern trends in mosque architecture in the northern cities of the United Arab Emirates, it has been found that square or rectangular plans remain the predominant form for prayer halls (in 96% of cases). The long side of the building, as a rule, forms the qibla wall with the mihrab located in the center, while the roofs are mostly flat. The main visual element that determines the typology of these mosques is often a minaret, which is often designed in an abstract or unconventional way. An in-depth study of the internal spatial organisation, lighting quality,

acoustic characteristics, comfort microclimate and sustainability of architectural solutions, taking into account the specificity of the local context, is emphasized **(Awad, 2021)**.

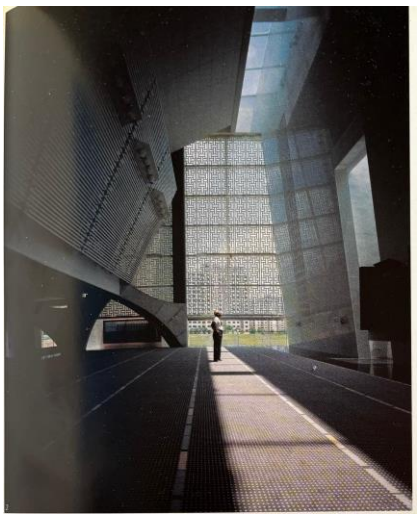
The building of the Alacaatli Uluyol Mosque (Ankara) demonstrates the rejection of the characteristic features of Ottoman cult architecture. Its architectural composition is based on a simple cube shape, but it also incorporates a traditional dome and a modern addition - a sun protection grid, due to Turkey's climate. The study conducted by the authors found significant differences of the analyzed mosques from the classical Ottoman typology, which was confirmed by a digital ranking of architectural parameters. This led to the development of a methodology for analyzing and categorizing cult architecture, which offers opportunities for further discussion **(Mertyurek & Demirbas, 2023)**.

The uniqueness of a building's image, its forms, decorative elements and symbolic content is maintained by culture and tradition, and on the contrary, can be lost as a result of unification and borrowing of global architectural solutions **(Abdrassilova et al., 2024, Abdrassilova & Danibekova, 2021)**. The studied examples of modern religious buildings demonstrate the introduction of progressive ideas of foreign architects. New approaches to design are used here, which noticeably differ from traditional architectural canons by their greater contextuality. As a result, new images of religious spaces have been formed, which often do not fit into the usual canonical framework.

Masjid Al Irsyad Mosque. General view **(Indonesia's unique mosques, 2019)**

Masjid Al Irsyad Mosque. View of mihrab **(Photo of the day, 2015)**

Assyafaah Mosque. General view **(Buck, 2006)**



Assyafaah Mosque. Interior **(Buck, 2006)**

Figure 1 – The search for regional identity in modern mosque architecture: examples from world experience.

Over the past two decades, Kazakhstan, as a young independent country, has shown an active desire for change and renewal in all areas of public life. This is especially true in the field of architecture, where Kazakh architects are increasingly turning to unconventional techniques,

methods, and forms. This trend is reflected in iconic buildings that are traditionally known for their sustainability and restraint when it comes to innovation.

Modern religious architecture, including Islamic buildings, also needs to be transformed to meet the challenges of our time. Its development should be based on a conscious departure from traditional canons, which encourages the search for new ideas rooted in a specific place's context - through its culture, natural features, and the formation of local symbols and artistic images. In **Figure 2** we present examples of mosques in Kazakhstan as experiments of progressive domestic architects. Going beyond the usual traditionalism, the authors proposed non-standard spaces of religious buildings, whose artistic and imaginative design reflect the regional identity and the spirit of the time.

Makhshur Zhusup Mosque. General view **(Kisamedin, 2012)**

Makhshur Zhusup Mosque. View of peshtak **(Kisamedin, 2012)**

Burabai Mosque. General view **(There is a beautiful mosque, 2019)**

Ryskeldi Kazhy Mosque. Interior **(Inside, 2018)**

Figure 2 - Modern architecture of mosques in Kazakhstan.

One of the examples of non-traditional architecture in Kazakhstan is the Mashkhur Zhusup Mosque in Pavlodar, designed by architects T. Abilda, N. Kabudaliev, S. Yusupov and S. Dautov in 2001. Despite the use of traditional elements such as domes, minarets and peshtaks, its design is not a direct copy of a classical pattern. Instead, it represents a modern interpretation of traditional architecture through the use of local symbols and unconventional spatial planning solutions. "… the mosque does not seem to be a repeat of the old pattern, … its image is new, … it easily corresponds with traditions, … but it is modern and expressive …" **(Kisamedin, 2012)**.

The tent-shaped silhouette of the building, based on an eight-pointed star, as well as dynamic domed shapes and the monumental peshtak with a corrugated surface, refer to the architectural heritage of Central Asia. In particular, these techniques are reminiscent of the mausoleums of the

Karakhanids, which combine the symbols of the Kazakh steppe - the Khan's tent and the warrior batyr - with sacred images that are important for local culture and help to create a unique architectural identity.

If we set aside the external similarities of the mosque to the usual traditional image and focus on enhancing the believer's sense of belonging to the sacred act of conversion to Almighty, and create conditions for a profound spiritual connection, it can lead to a shift in the three-dimensional and artistic design of mosques, focusing on the inner experience of the person. At the same time, regional identity plays an important role, allowing mosque architecture to not only preserve its spiritual significance, but also reflect the unique cultural, semantic, historical, and climatic characteristics of a particular area, forming a truly authentic and harmonious sacred space.

The architecture of Burabai Mosque (BI Group, 2019) in the Shchuchinsko-Borovsky resort zone, designed by the company, is expressed in a cubic form (There is a beautiful mosque, 2019). The choice of this form is due to the roots of the reference to the cube/platform, its symbolic meaning going back centuries.

In traditional Kazakh architecture, cubic forms often formed the basis of religious buildings. One example is the mausoleum of Aisha-bibi a cubic shaped building with a cone-shaped dome with richly decorated walls **(Glaudinov, 2019)**. According to the Kazakh scholar E. Baitenov, the cubic form is a kind of spatial archetype ‘platform’. A compact centric volume (of a square, rectangle, circle, polygon) has traditionally been the basis of the volumetric and spatial structure of buildings, including religious buildings such as mausoleums, mosques, sacral complexes **(Baitenov, et al., 2019, Baitenov, 2024)**. Thus, the shape of a cube/platform symbolized stability, balance and solidity, a symbol of the earth. As a culturally fixed archetype, the cube reflects the spiritual, ethnic and historical basis of Kazakh architecture, reflecting the mentality and connection with the traditional image of dwelling - the yurt. Using the example of the Burabai Mosque, reference to this archetype contributes to the integration of the building into the cultural landscape and the actualization of the modern appearance of religious buildings in new interpretations in order to strengthen regional identity.

Let's consider the trend of rethinking traditional forms in the work of modern architects in Kazakhstan, taking into account cultural archetypes and the use of modern technologies. The Yryskeldi Kazhi Mosque’s building in Astana (arch. S. Dzhambulatov, 2018) uses non-standard shapes, such as triangular walls and a dome, which image is an inverted lotus flower. This postmodern style meets the current demand for zero consumption of non-renewable energy **(Inside, 2018)**. The use of solar panels helps solve the environmental problem by reducing energy costs and provides a modern approach to integrating traditional symbols into modern architecture, shifting the focus from traditional Islamic architecture towards innovation.

The last two examples considered are examples of a minimalist approach, which seem to reflect current trends in architecture. However, simplicity of form, restraint, and modesty in the design of sacred spaces have always been inherent in the local population due to the influence of Sufism. Sufism originated in the 7th-9th centuries as a mystical and ascetic branch of Islam and had a significant impact on the spiritual culture and architecture of Kazakhstan.

In cult architecture, this was reflected in the desire to create private, meditative spaces that encourage inner concentration and spiritual purity. Sufi ideas were widely spread in the region due to the efforts of Khoja Ahmed Yasawi, the founder of the Turkic Sufi tradition, who blended Islamic spirituality with traditional nomadic customs. As a result, a unique architectural style emerged, characterized by simplicity, profound symbolism, and ascetic spatial planning **(Abdrassilova, Murzagaliyeva & Kuc, 2021, Orynbekov, 2005)**.

Figure 3 shows how simple forms of cube, pyramid, as archetypes (according to the research of E. Baitenov) in Kazakhstani architecture serve as a bridge between tradition and modern architectural solutions, strengthen cultural identity and reflect the aspiration to innovation.

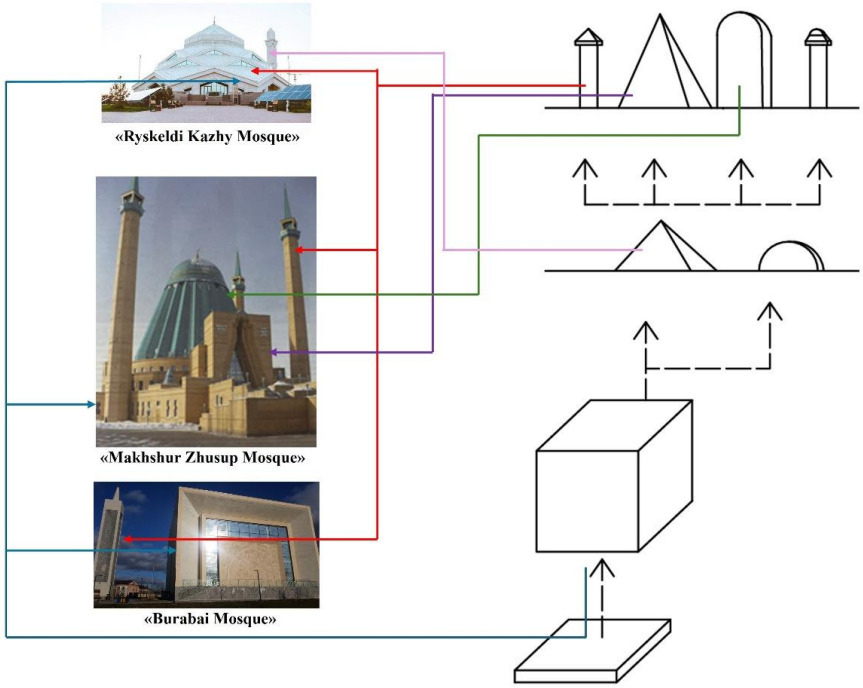


Figure 3 – Archetypes in modern interpretations of mosque architecture in Kazakhstan (authors' material).

5 CONCLUSIONS

Studies have shown that in the conditions of globalization the modern mosque is now open to change, the architectural appearance of which is formed at the intersection of tradition and innovation, past and present. The essential importance of this aspect is that the architecture of religious buildings can be enriched by taking into account the local socio-cultural identity and spatial environment. A delicate correspondence to the local multinational and multicultural environment as in the case of the Assiaf Mosque in Singapore, or consideration of the philosophical underpinnings of ancient traditions and beliefs such as Sufism can be an important guideline in the search for authentic architectural expression. Contextualized architecture of mosques, in turn, contributes to the formation of a mature and conscious society, aware of its own religious and socio-cultural identity. On the example of a developing country like Kazakhstan, this direction becomes especially relevant when architecture becomes an important element reflecting the state priorities and missions aimed at strengthening the country's position in the international arena. Thus:

1. In the conditions of growing globalization processes in Kazakhstan, regional architecture based on the adaptation of artistic image and form to the local context is called to solve the problem of revival of traditions, preservation of identity with strengthening of identity;

2. Taking into account the local specifics of multinationalism and multiculturalism of the environment will ensure cultural relevance, achieving balance and inclusiveness;

3. Mandatory integration of ecologically oriented modern technologies and architectural trends into the system of designing religious buildings will support compliance with the global trend - sustainable development.

4. Dialogue with the environment, the ability to adapt to changing conditions of the time and active interaction with the local cultural context will allow to go beyond the established norms in the design of modern mosque buildings balancing between globalization and the search for regional identity.

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RESEARCH ARTICLE

EXPERIENCE OF RENOVATION OF CITY PARKS OF THE POST-SOVIET PERIOD

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Abstract. *Parks of culture and recreation occupy a special place in maintaining the ecological balance in the urban environment, due to their location and large territory. However, in the existing park facilities, opened in the Soviet period, the condition of the appearance has noticeably deteriorated, the former grandeur of architectural forms and landscapes has been lost. With the change in ownership, the multifunctionality and accessibility of object zones located in the park space has been lost. The study examined the developments of designers in the field of architectural and landscape design, specialists studying the sociological, communication, technological and economic issues of the functioning of public spaces in the urban environment. The relevance of this study lies in the need to reboot the architectural and landscape design of parks, which must meet the requirements of the time; in the development of a certain approach to the application of pre-project analysis methods for the renovation of parks as public spaces. The study provides a brief historical background on the origin and development of park culture, and examines in detail the principles and methods of designing park areas at the present stage. Using the method of environmental pre-project analysis, a new view of the park is proposed as an environmental object that ensures the full satisfaction of the needs of a modern person. The presented experience of park renovation is interesting and accessible for use in practical activities when creating a multifunctional aesthetically complete environment based on a natural complex.*

Keywords: *Renovation, park space, pre-project analysis, environmental design, placemaking.*

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ҒЫЛЫМИ МАҚАЛА

ПОСТКЕҢЕСТІК КЕЗЕҢДЕГІ ҚАЛАЛЫҚ САЯБАҚТАРДЫ ЖАҢАРТУ ТӘЖІРИБЕСІ

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Аңдатпа. *Қалалық ортада экологиялық тепе-теңдікті сақтауда мәдени-демалыс саябақтарының орны және аумағының үлкендігі ерекше орын алады. Дегенмен, бұрынғы кеңестік кезеңде ашылған саябақ нысандарында олардың сыртқы келбетінің жағдайы айтарлықтай нашарлап, сәулет нысандары мен ландшафттарының бұрынғы салтанаты жойылды. Меншік нысандарының өзгеруімен саябақ кеңістігінде орналасқан нысандар аумақтарының көпфункционалдылығы мен қолжетімділігі жойылды. Зерттеу сәулет-ландшафттық дизайн саласындағы дизайнерлердің, қалалық ортадағы қоғамдық кеңістіктердің жұмыс істеуінің социологиялық, коммуникациялық, технологиялық және экономикалық мәселелерін зерттейтін мамандардың әзірлемелерін зерттеді. Бұл зерттеудің өзектілігі мынада: саябақтардың уақыт талабына сай болуы тиіс сәулеттік-ландшафттық дизайнын қайта жүктеу қажеттілігі; саябақтарды қоғамдық кеңістік ретінде жаңартуды жоба алдындағы талдау әдістерін қолданудың нақты тәсілін әзірлеуде. Зерттеу саябақ мәдениетінің пайда болуы мен дамуы туралы қысқаша тарихи мәліметтерді береді және қазіргі кезеңдегі саябақ аумақтарын жобалаудың принциптері мен әдістерін егжей-тегжейлі қарастырады. Жобалау алдындағы экологиялық талдау әдісін қолдана отырып, қазіргі адамдардың қажеттіліктерін толық қанағаттандыруды қамтамасыз ететін экологиялық объект ретінде саябаққа жаңа көзқарас ұсынылады. Саябақты жаңартудың ұсынылған тәжірибесі табиғи кешен негізінде көп функционалды, эстетикалық құнды ортаны құру кезінде практикалық қызметте пайдалану үшін қызықты және қолжетімді.*

Түйін сөздер: *Жаңарту, саябақ кеңістігі, жобаға дейінгі талдау, қоршаған ортаны жобалау, орналастыру.*

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НАУЧНАЯ СТАТЬЯ

ОПЫТ РЕНОВАЦИИ ГОРОДСКИХ ПАРКОВ ПОСТСОВЕТСКОГО ПЕРИОДА

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Аннотация. *Особое место в поддержании экологического равновесия в городской среде занимают парки культуры и отдыха, в силу своего расположения и значительной территории. Однако, в существующих парковых объектах, открытых еще в советский период, заметно ухудшилось состояние внешнего вида, утрачено былое величие архитектурных форм и ландшафтов. С изменением форм собственности, утрачена многофункциональность и доступность объектовых зон, расположенных в парковом пространстве. В ходе исследования рассмотрены разработки дизайнеров в области архитектурно-ландшафтного дизайна, специалистов, изучающих социологические, коммуникационные, технологические и экономические вопросы функционирования общественных пространств в городской среде. Актуальность настоящего исследования заключается: в необходимости перезагрузки архитектурно-ландшафтного дизайна парков, которые должны соответствовать требованиям времени; в выработке определенного подхода к применению методов предпроектного анализа реновации парков, как общественных пространств. В исследовании дана краткая историческая справка о зарождении и развитии парковой культуры, детально рассмотрены принципы и методы проектирования парковых зон на современном этапе. Методом средового предпроектного анализа, предлагается новый взгляд на парк, как на средовой объект, обеспечивающий полноценное удовлетворение потребностей современного человека. Представленный опыт реновации парков, интересен и доступен к использованию в практической деятельности при создании на основе природного комплекса многофункциональной эстетически полноценной среды.*

Ключевые слова:. *Реновация, парковое пространство, предпроектный анализ, средовой дизайн, плейсмейкинг.*

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Авторы заявляют, что конфликта интересов нет.

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1 INTRODUCTION

In modern conditions, a park zone is an integral part of the city, intended for mass and affordable recreation of city residents.

From Wikipedia: "Parks of culture and recreation are usually located in populated areas on the territory of garden and park or forest areas. Large parks in the Soviet period often had their own summer theaters, lecture halls, reading rooms, attractions, dance halls, as well as rental bases for various sports and cultural equipment. Shooting ranges, children's towns and sports grounds operated in the parks, in winter - ski bases and skating rinks, children's towns and playgrounds. Boat stations operated on the reservoirs near the parks.

Parks of culture and recreation carried out mass - political, cultural and educational and physical education - health work. Exhibitions, folk festivals, state and sports holidays were held here, performances, concerts and films were organized in summer theaters. The parks also hosted various courses and clubs, health and sports groups".

This study, using a number of post-Soviet parks as an example, offers an analysis and development of conceptual proposals for the renovation of public space in modern conditions and in accordance with international standards.

The study is based on the study of the works of domestic and foreign scientists and specialists in the field of architectural and landscape design, including as applied to the design of park areas.

Along with field research, information was collected and processed, the main conflicts of the park environment were identified using the method of environmental pre-project analysis and their solutions were worked out in the process of thematization.

The toxicity of the existing infrastructure of parks opened in the twentieth century is shown. The problem is that despite the presence of a recreational place, there is a complete lack of its functionality. Moreover, there are parks that are degrading in an ecological and social sense, becoming a dangerous place for city residents.

Using analog design and collage modeling methods, taking into account the world experience of architectural and landscape design, elements and innovative ideas that can be applied in the course of park renovation have been selected. and will introduce modern trends in demand by all categories of citizens.

The relevance of this study is due to the combined approach to the application of domestic and foreign experience in the field of improvement of ecological zones in the urban environment, which is of interest to specialists in architectural and landscape design, as well as specialists working in the field of communication and information technologies.

For interested specialists, a selection of proposals for the use of new forms of analysis in the preliminary design is offered, and the attention of developers is focused on individual zones for special categories of visitors.

The main risks and requirements for park safety in the urban environment are identified. Solutions to problems of different mobility and socialization are proposed. Particular attention is paid to the creation of an inclusive case of accessibility of stay of people with limited mobility in the natural environment.

The study shows the use of placemaking and the practice of participation in the project. Using the opinion of city residents in updating the appearance of the park and creating infrastructure will provide additional ideas for transforming existing objects in the interests of visitors. This practice has a positive response among the population, attracts additional investment from the private environment of small and medium businesses.

When zoning the park, it is necessary to resolve issues related to the objects: organizing various cultural events, entertainment and shows that meet the needs of various groups of park visitors; holding ethnocultural events, exhibitions, fairs of arts and crafts; promoting scientific and educational knowledge, achievements of science, technology, art and literature; developing physical education and sports; organizing a variety of recreation for visitors - active and passive forms, in summer and

winter. Much attention when making landscape decisions should be paid to landscaping, the so-called quiet recreation areas: paths, pedestrian, running and cycling paths, and ski routes in winter.

Also, as one of the zones, it is necessary to provide a children's location for younger children, with the possibility of organizing a variety of recreation in a playful way.

A specific aspect in the development of the concept of the park zone is introduced by motives of ethno-cultural elements based on the historical and cultural features of the arts and crafts of Kazakhstan. In general, the study examines the general patterns of application of the basic principles and methods of architectural and planning pre-project analysis, their relationship with the renovation of parks, with adaptation to modern requirements.

The use of various innovative technologies will help to create modern architectural forms and landscape design in three-dimensional space.

It is in this area that such conditions are created for the population that ensure a high standard of living. Thus, pre-project development offers conditions for a healthy, comfortable, convenient life for both an individual and all residents of the urban environment.

The purpose of this study is to develop the main architectural and planning directions for the renovation of parks in the post-Soviet period.

The value of the study lies in the creation, on the basis of the presented work, of a template module of a preliminary design solution for full or partial use in the renovation or design of the construction of park areas.

2 LITERATURE REVIEW

Today, it is impossible to imagine urban space without parks – they have become a multifunctional eco-platform in the lives of city dwellers. In some sources, the prototypes of park recreational areas were created by the Persian kings, while others mention their origin in ancient China. The first parks and gardens appeared in the Baroque era in France. Thus, the Royal Tuileries Garden at the Louvre was opened to the public in the 17th century. Then similar park areas appeared in Europe. At first, park space was distinguished by aristocratic forms of design, which implied that visitors observed a certain etiquette. Publicly accessible city parks appeared in the 19th century.

During the reforms of Baron Osman in France, the Bois de Boulogne and the Bois de Vincennes were landscaped as parks, where new boulevards with trees, walkways and gazebos were created. In the Buttes Chaumont Park in Paris, the complex relief is already arranged in a romantic style, with small architectural forms and attractions. Among the first architects of urban park spaces, Frederick Law Olmsted in the USA should be noted, defending the ideas of accessible recreation for the rich and the poor. In Austria, landscape design was represented by the artist Joseph Selleni and the chief city gardener Rudolf Siebeck, the founders of the Stadtpark - an important part of this park was a large cafe. In the 20th century, parks acquire the multifunctionality characteristic of modern times, they combine nature, entertainment, sports, culture and ideology. As an example, we should consider Gorky Park in Moscow (Russia), created in 1928. At different times, architects Konstantin Melnikov, El Lissitzky, Alexander Vlasov and Georgy Shchuko worked on the park project. The park was designed taking into account the suggestions of workers, uniting the territories of Neskuchny Garden and the All-Russian Agricultural Exhibition.

An interesting multifunctional development is La Villette Park in Paris (France), created in 1982 by architect Bernard Tschumi and philosopher Jacques Derrida. The architectural idea of the park consists of three independent layers with different thematic loads, united into a single integral space.

In the generally accepted architectural hierarchy, parks are divided into several types: natural park, botanical park, arboretum, zoological park, forest park, national park, landscape park, amusement park, park of culture and recreation.

The authors Guk T.N., Frolova Yu.V., Semenkova E.V. (**Guk et al, 2018**) in their works consider the division of parks into the following types: open-parterre options, where the presence of flower beds, flower gardens, lawns and living decorative hedges is most prevalent; closed - the presence of

trees and densely growing shrubs predominates, which, thus, allows isolating from noise, exhaust gases and other interferences; with reference to a building structure or object - such squares and parks perfectly decorate high architectural monuments, modern buildings and are also designed to ennoble the central squares of the city.

In landscape design, there are: a regular park (French or geometric, with well-groomed alleys, flower beds, pools of regular shape) and a landscape park (English or natural, with a natural landscape). Park design styles: classical, which is represented by the Renaissance, French and English; modern in the form of minimalism, loft and hi-tech.

Vergunova A.P. (**Vergunov, 1980**) in her works is of the opinion that in the traditional sense, the ultimate goal of designing landscape objects, including gardens and parks, was to create a certain artistic image of the park, a park ensemble in which "nature, architecture and man are harmoniously interconnected."

Rozenson A.A. (**Rozenson, 2007**) believes that the modern practice of designing public space is aimed not so much at obtaining a highly artistic object, but at creating a harmonious and comfortable environment for a real person, capable of "treating a person in a humane manner."

According to Gelfond A.L. (**Gelfond, 2019**): "public space is a public space for communication and social activity, organized in accordance with the dominant function." Stepanchuk A.V., Gafurova S.V., Latypova M.S. (**Stepanchuk et.al, 2020**) adhere to the idea that public space is considered not just as an additional element of the city, but as a component that changes its appearance, like an “urban living room”. The perception of the holistic image of the city and its local landscape objects is formed on the basis of the significance and identity of the place (**Treija et.al, 2020**).

This statement has many followers who believe that the design of public space should include such types of analysis as urban planning, historical, analysis of the cultural potential of the territory, local community (community), with the definition of target audiences and identification of their needs. Based on the results of a comprehensive pre-project analysis, a complete picture of the local identity of the territory is formed, its development potential is revealed, problems are identified and the main ways of solving them are determined. The reorganization of urban public spaces should be carried out while maintaining identity (**Salakhova et.al, 2022**).

It is important to endow each space with an individual architectural and figurative solution in order to consolidate it in the visual perception of a person in the urban structure as a whole. It is extremely important, "in the process of designing public spaces, to take into account the peculiarities of the formation of the symbolic identity of the city, to identify and preserve the characteristic features of the city's uniqueness" (**Jaszczak et.al, 2021**). Some architects and designers, when developing park projects, put the economy as the dominant factor, while others put the ecology as the dominant factor. There are views that combine both directions. “Parks, squares and other typologies, competently integrated into the urban structure, create a single public and recreational framework, shaping the image of the city, transforming adjacent territories and having a positive impact on its economy” (**Kaplan, 1984, Grundlingh, 2017, Abbott, 2020**). This interpretation of the urban environment is aimed primarily at improving the ecology and reducing the negative impact of the metropolis. At the same time, “the viability of the urban ecosystem, as well as the natural one, is ensured by a combination of various components” (**Stepanchuk et.al, 2020**).

It should be noted that as a result of various approaches to design, most recreational spaces of the post-Soviet period often simply do not meet the requirements of the modern world. Thus, at the level of internal and external appearance, small architectural forms have an archaic appearance, landscape design is presented in the simplest forms, zoning is practically absent, the infrastructure is technologically outdated. Such territories require updating and an integrated approach for comfortable and meaningful recreation of citizens. An integrated approach to the organization of spaces is the ability to create an environment and provide a scenario for the social life of a place. Design is characterized, first of all, by the fact that during work on the transformation of the territory, processes are launched that will develop after the end of the project (**Ivankina & Perkova, 2018, Shchenkov & Antonova, 2020**).

Currently, the design of park objects is actively developing in the process of urbanization of modern cities, enriched with new approaches, for example, environmental design methods: problematization and thematization of the design task. This allows taking into account a number of requirements for the urban environment, such as functional, social and environmental, during the design process. The created park ensemble assumes harmoniously interconnected “nature, architecture and man” (**Hayward & Weitzer, 1984, Cohen, 2009, Dmitriychuk & Denisova, 2019**).

The study, as the most effective approach, presents the method of environmental pre-project analysis, which allows you to look at the park not only from the point of view of the natural complex and architectural landscape ensemble, but also from the position of the environmental object.

It can be safely stated that “without environmental analysis, only in rare cases do holistic natural, artistic and functional dominants develop simultaneously in a single park complex.” In most cases, these are long years of “adaptation”, “grinding in” of contradictory situations, trends and processes (**Sidorenko, 2022**). Solutions to the problems of "grinding and adaptation" are described in the review by Anel Moldakhmetova: "According to placemaking expert Guillermo Bernal, director and founder of the Lugares Publicos bureau, when creating a concept for a public space, it is important to ask people not about the objects they would like to see there, but about the functions and scenarios they need. We need to discuss not the color, shape, style and size, but the emotions, activities and scenarios for using parks as public spaces" (**Moldakhmetova, 2019**).

Having studied domestic and foreign materials devoted to the architectural and landscape design of park spaces, we can state the effectiveness of the integrated use of methods: environmental pre-project analysis, by analogy, collage, placemaking and participation. This symbiosis of methods will satisfy the wishes of society, and on the basis of scientific and specialized knowledge create an environmentally useful, and most importantly, multifunctional park space within the urban system.

3 MATERIALS AND METHODS

The study included a set of methodological activities aimed at developing an algorithm for pre-project analysis of architectural and planning renovation of post-Soviet parks.

The study is based on the method of environmental pre-project analysis, through problematization and thematization of the project assignment. Using field research (in the form of a survey, observation, photo recording and documentation of problem points of the existing type of park), as well as collecting and processing information, the main conflicts of the park environment were identified.

When working through the problematization, groups of conflicting contradictions were identified and directions for their solutions were developed.

The solution of social conflicts can include the search for compliance of environmental zones, which take into account the interests of age and social groups of the population.

Consideration of the functional conflict is intended to unite the needs of different groups of the population in one territory when visiting the park. For example, to provide separate recreation areas for playgrounds, walking areas for different ages and mothers with strollers, bike paths and dog walking. The solution of visual-aesthetic and artistic conflicts is in the plane of satisfying the aesthetic and spiritual needs of visitors, through the harmony of the natural landscape and architecture of the park space.

Resolution of the environmental conflict consists in identifying and eliminating possible negative environmental impacts on the park landscape. For example, the close location of a highway with toxic emissions, failure to comply with the requirements for maintaining the drainage cover of soil and water bodies.

Understanding the communication and information conflicts will help make the public place more accessible to visitors. For example, the presence of two or more entrance groups, proximity to a transport interchange, the presence of parking lots, the location of recreational placement maps and signs for orientation in the park space.

Accessibility of park visitors to modern technologies (availability of power supply bases, Wi-Fi, LED screen) is a solution to the technological conflict.

In addition, when designing, it is imperative to take into account the climatic features of the location of park areas, consider the presence of open, closed and covered facilities.

When thematizing the design task, a quantitative and qualitative analysis of existing architectural and landscape solutions was carried out, and issues of zoning the park space were worked out. In the course of a comparative analysis, as well as by the method of designing by analogies and collage modeling, ways of design solutions were proposed.

The study was conducted on the example of a comparative analysis of the general plan of the Alash Arystary Park (formerly the Park of the Fighters of the Revolution, 1957-2023), with a study of the opinions of residents of the city of Kokshetau and the Akmola region in social networks and through an individual survey. The research material is partially based on archival data of the Kokshetau History Museum.

4 RESULTS AND DISCUSSIONS

The Alash Arystary Park, previously known as the Fighters of the Revolution Park until 2023, is one of the oldest recreation areas located in the city of Kokshetau in the Akmola region (area of the territory is 24 hectares).

According to the materials of the City History Museum, the creation of the Park of the Fighters of the Revolution dates back to 1918, when General Annenkov's White Guards shot about 60 Bolsheviks from Kokshetau here. The history of the monument is notable for the fact that the burial place of the fallen revolutionaries was originally located 100 meters to the west. However, in 1957, by decision of the executive committee of the Kokshetau City Council of People's Deputies, the remains were reburied to their current location and a modest obelisk was erected. In 1967, in honor of the 50th anniversary of the Great October Revolution and in memory of the fallen heroes, a monument was erected, which still stands today (**Figure 1**).

The archives of the museum fund indicate that the authors of the monument were sculptor V.I. Kostin from Donetsk and architect V.K. Romanko from Kokshetau. The monument was erected with funds from the city's workers, and the figures were made at the Kokchetav Instrument-Making Plant.

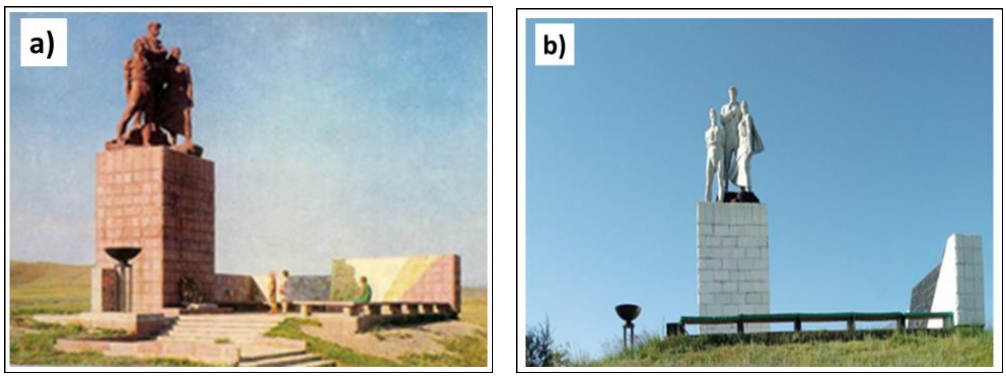

Figure 1 – View of the monument to the Fighters of the Revolution: **a)** – 1967 [photograph from the archive of the Kokshetau city history museum]; **b)** – 2024 [material of the authors].

From the description of the monument: "On a high granite pedestal is a bronze sculptural group of three reinforced concrete figures - two men and a woman. The total height is 11.5 meters. The area of the stylobate is lined with concrete slabs. On the southern side is a bas-relief depicting an episode of the battle and a bas-relief symbolizing the exploration of space, the idea of the struggle for peace. To the left of the monument is a bowl for the eternal flame. On the stele located on the right side of the monument are words from the poem by Robert Rozhdestvensky "Letter to the Thirtieth Century" (**Museum of the history of the city of Kokshetau, a.d. 03.09.2024**).

The monument occupied a central place in the park, where, along with the park area, a children's railway was installed in Soviet times. **Figure 2** shows the carriages of the "Young Kokchetavets" train and the 1.8 km long circular railway track (the children's railway station operated until 1995, and by 2001 it was completely dismantled and liquidated).

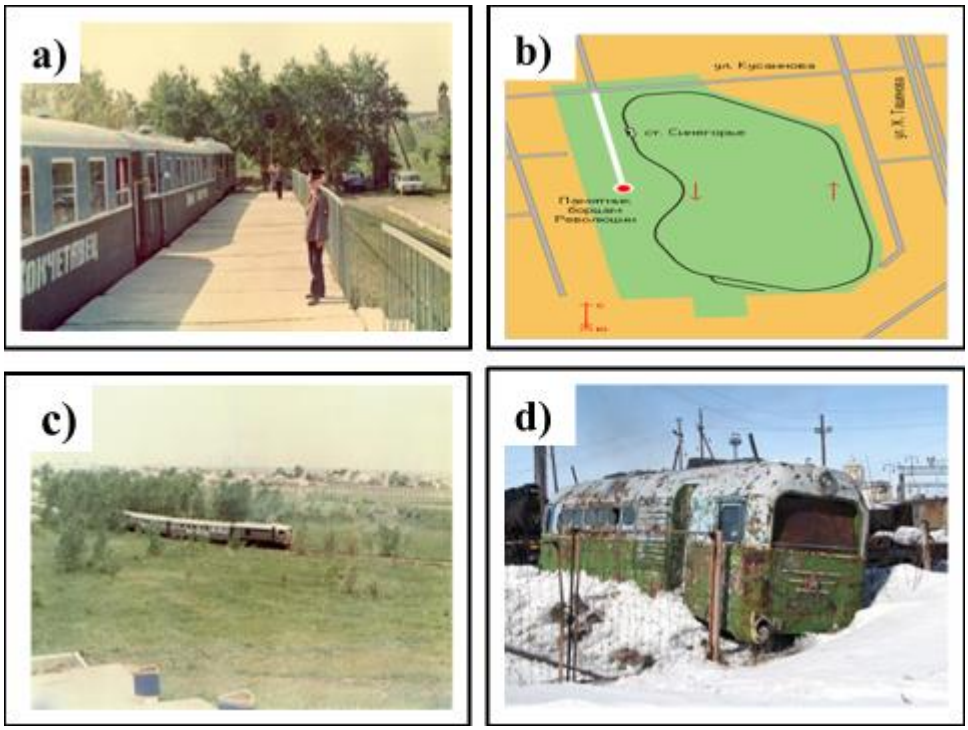

Figure 2 – Views of the "Young Kokchetavets" train of the children's railway: **a)** – at the Sinegorye station; **b)** – diagram of the Children's Railway; **c)** – on the section [photo by M. Helme, 1991 from the Museum's archive]; **d)** – a diesel locomotive of the Children's Railway at the locomotive depot [authors' materials].

There was also a football court here, which in winter became a hockey field and an ice rink. According to old-timers, the park was a favorite place for citizens to relax, athletes trained here and city holidays were held.

In the 90s of the twentieth century, the park area lost its former significance and cultural appearance. So, without proper care, the children's railway was gone, everything was overgrown with weeds. At the same time, citizens have repeatedly raised the issue of restoring the park.

Since 2015, the Fighters of the Revolution Park has begun a second life, it was decided to make an updated park of culture and recreation with a roller ski track on the site of the park. **Figure 3** shows the general plan for the reconstruction of the park. All subsequent years, adjustments were made to this plan. In 2023, by the 200th anniversary of the city, work was completed on the project, on which about 900 million tenge had been spent since 2015.

The initial project included the following: construction of an entrance area, a sports and utility complex, and a public toilet; fencing of the area; installation of external utility networks; placement of a roller ski track, bridge, pond, and parking lot. Landscape design included: arrangement of flower beds and lawns; planting of trees and shrubs; installation of small architectural forms; covering of paths with paving stones. Through public-private partnership, the park was planned to accommodate: a stele, a youth palace, a water park, an indoor gym, a swimming pool, volleyball and basketball courts, football pitches, a motorcycle track, an amphitheater, a Ferris wheel, a rock garden, a cafeteria, an ethno zone, and attractions.

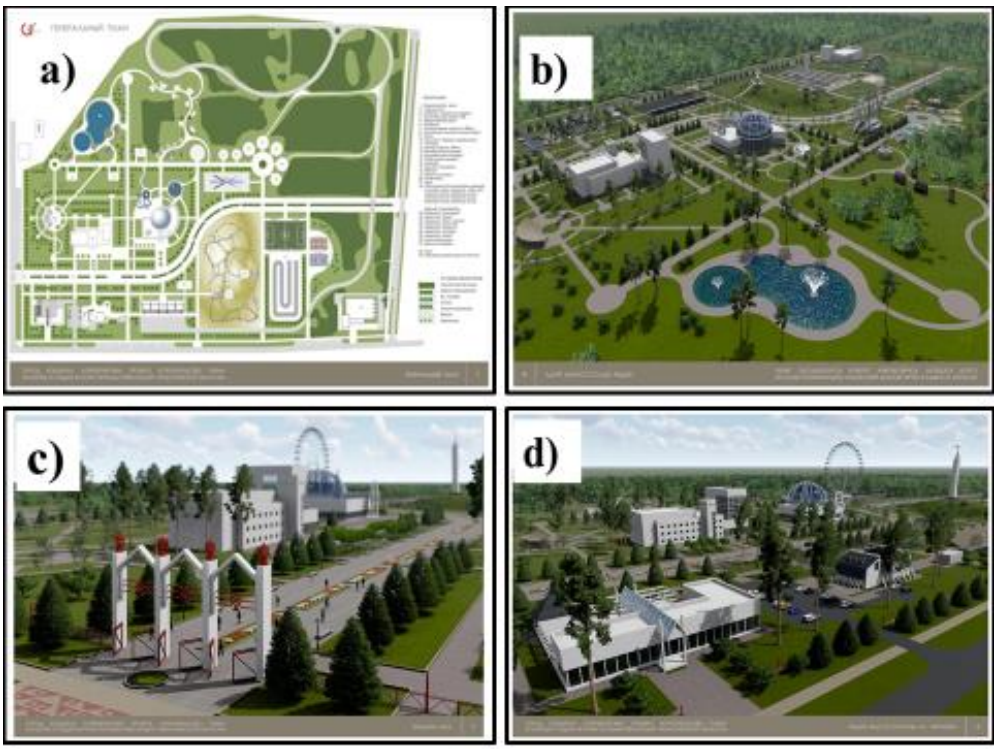

Figure 3 – a), b), c), d) – Types of the master plan
"Construction of a park of culture and recreation in the park "Fighters of the Revolution" of the Akmola region" (since 2023 – park "Alash arystary") [authors' materials].

As a result of the project adjustment, the construction of the bridge and pond was replaced by the installation of pedestrian and bicycle paths, children's and sports playgrounds.

A study of social networks and a survey of city residents showed an ambiguous attitude towards the reorganization of the park. The architectural plan, according to park visitors, does not correspond to the actual object. Visual inspection and photo recording of the current state of the park confirm the problematic nature of the object (**Figure 4**).

Figure 4 – a) collage diagram of constructed and unconstructed objects, from those planned by the general plan [authors' materials].

When comparing the condition of the park space, it should be noted that during the reorganization period (2015-2024), the central alley with many trees was cut down in the park. The monument to the fighters of the revolution was left unchanged, but needs reconstruction. On the positive side, a children's playground, a playground with sports horizontal bars, a skateboarding area, a sports and utility complex building were built, and a large number of paths were paved with paving stones. At the time of the study, there was no landscape design in the park space at all, which is clearly shown in **Figure 5**. Thus, the lawns are overgrown, flower beds are missing, and the planted conifers are in a non-textured condition. The paving stones on the main alley and paths have crumbled in places and are overgrown with grass. The children's playground surface has partially become unusable, and there are no goals on the football field.

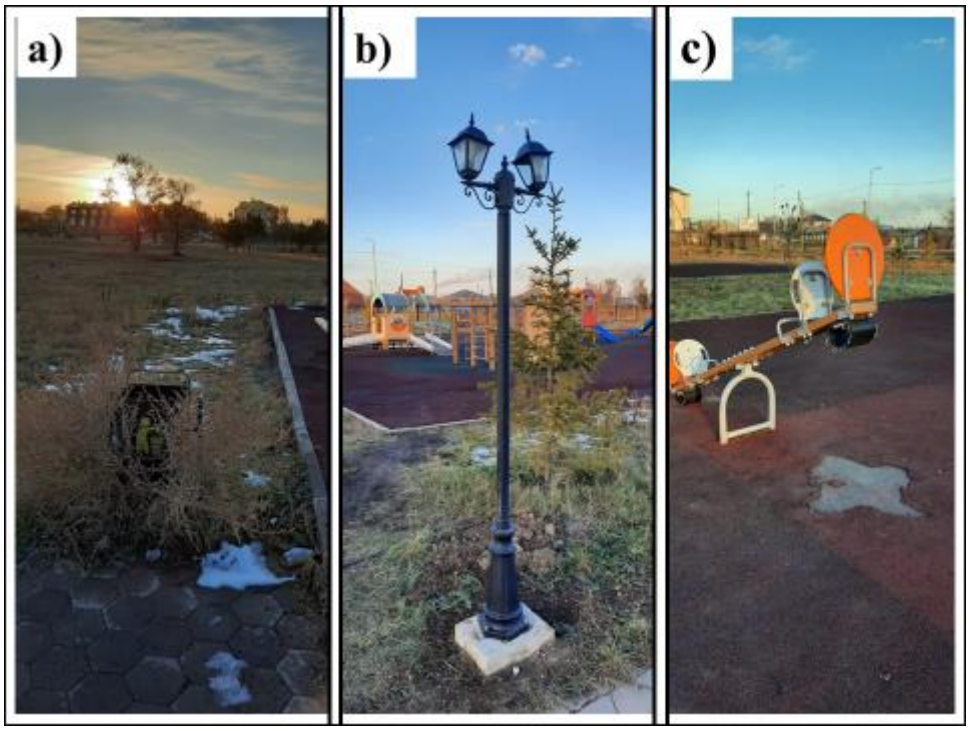

Figure 5 – typical violations of the quality of the park reconstruction: **a)** views of the overgrown grass lawn and trash can; **b)** view of the playground, broken lampshade, unkempt lawn and spruce seedlings; **c)** defects in the tartan covering of the playground [authors' materials, 2024].

In general, the arrangement of the park for the most part does not coincide with the general development plan, zoning was carried out without taking into account the social and functional load, the requirements for the visual and aesthetic appearance of the public space were not met. The infrastructure of the park was partially established, including external utility networks for electricity, heat, telephone, water supply and sewerage, a well was installed, the fencing of the facility was reconstructed. At the same time, the reconstruction was carried out without taking into account the communication, information and technical load on the park, as an object of mass visitation of different age groups of the population. Thus, it can be concluded that, using the example of the Alash Arystary Park (formerly the Bortsam Revolutsii Park, 1957-2023), parks of the post-Soviet period have lost their former significance; their reconstruction was often carried out without proper development and compliance with master plans and architectural and landscape requirements, according to the principles of uncontrolled development of funding due to the placement of small forms of "yard level" (children's slides, exercise machines, a football field).

Regarding the analysis of the thematization of the master plan for the reconstruction of the Alash Arystary Park, the authors of the study propose to revise it using existing analog design

solutions, from which the most suitable techniques and functional processes for the designed park should be selected.

Using environmental analysis, a study was conducted to develop a pre-project design or adjust the master plan of the park zone (in this case, making adjustments is more appropriate, since construction has not yet been completed).

The long term of the existing project, constant deviations from the plan and the inadequate quality of the already erected objects indicate the lack of proper technical, author's and state control over the implementation of the general plan of the park zone.

In the future, according to the project, within the framework of a public-private partnership, it is planned to place in the park: a stele, a youth palace, an indoor sports hall, a swimming pool, a water park, a moto track, volleyball and football courts, an amphitheater, an ethnic village, attractions, a Ferris wheel and a cafeteria with an inner courtyard. In some sources, city officials discuss the possible placement of retail facilities on the territory of the park.

According to the basic principles of placemaking, the opinions and wishes of citizens, their vision of the development and functionality of this public place became the focus of the study.

For example, the existing playground and the area with exercise machines, according to the suggestions of visitors, should be made less traumatic. During the survey, many complaints and requests were received to install more children's play equipment, as well as to make sports equipment multifunctional in terms of physical activity.

Another desire of citizens was to launch a mechanical, colorful train along the main alley and paths for excursion rides around the park area for children and older visitors.

A football field without goals, according to the current plan, is a universal site where you can play mini football or gorodki. At the same time, it would be more productive to expand the football field and make a court, and in winter - a flooded skating rink and a hockey field.

The survey and the analysis of social networks show a complete denial and negative attitude of citizens to the placement of retail facilities and restaurants on the territory of the park.

Questions arise about the feasibility of building a Ferris wheel, since there is one in the central park of the city and it is in demand by only 25%. More than 80% of the respondents surveyed positively consider the placement in the park space of: a youth palace, an indoor sports hall, a water park, a motorcycle track, a volleyball and football field, since among the residents of the adjacent residential area there is a need for the functioning of these facilities.

The survey participants showed significant interest in the organization of places of mass recreation and landscape design of natural zones. In **Figure 6**, in the form of a diagram - collage, the changes proposed in the park renovation project are presented.

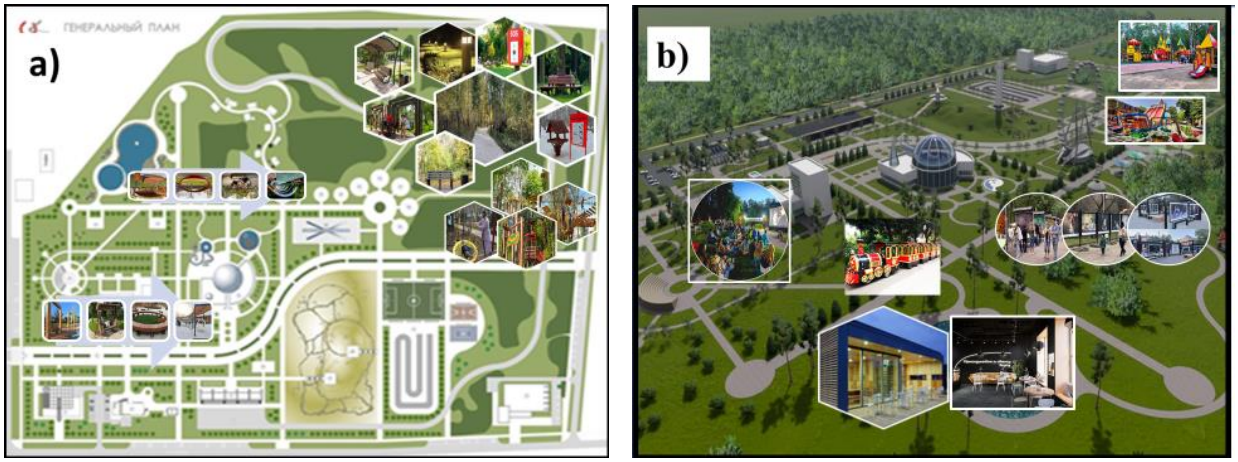

Figure 6 – a collage diagram of proposals for the park renovation plan for the placement of:
a) – small architectural forms in a natural forest area for its comfortable and safe visiting; - a rope town; - a quiet recreation area; - benches, benches and swings of various shapes; **b)** – an LED screen in the amphitheater area; - an open-air exhibition in the ethno-village area; - a typical cafeteria [authors' materials, 2024].

A significant area of the park zone is occupied by a natural forest, which needs to be made more accessible, comfortable and safe for visitors, while maintaining its recreational purpose. Using landscape design tools, the forest (without cutting) should be divided into pedestrian paths, lighting should be installed (paths and forest glades), good benches, picturesque bridges over ravines, urns, feeders for animals and birds should be placed.

In the forest area adjacent to the sports facilities, a rope town should be located, which will be especially appreciated by lovers of active recreation. The opposite part, overlooking the rock garden, is well suited for visitors of middle and older age categories for a place of relaxation in the form of yoga or doing a set of exercises.

Parallel to the main park alley, make indentations where benches, benches, swings will be placed, the design of which can be varied. It is proposed to announce a competition among residents or enterprises of the city for the development and installation of these small architectural forms. In the area of the ethno-town, to maintain the national flavor and create a creative mood, it is proposed to install indoor rows of exhibitions and fairs-sales of decorative and applied art items. The path leading from the main alley to the ethno-town should be decorated with stand structures of open-air exhibitions, where you can demonstrate the works of artists, photographers, place information about the history and achievements of the city and the region.

The idea of collective recreation will work great if you install an LED screen in the amphitheater area - an open-air cinema with free viewing. Firstly, this will solve the problem of free space when concerts or other festive events are not held. Secondly, with a good selection of the repertoire, the cinema will become a place of attraction for different ages. Visitors attracted by ticketless viewing will certainly be interested in other attractions of the park.

Considering the fairly large area of the park space, one of the main tasks of the public place is the presence of a main entrance and two side entrance groups. In addition, one stationary toilet is not enough, it is proposed to install bio-toilets or stationary toilets for visitors in the perimeters of the boundaries of the target spaces (in the zone of visibility and accessibility, approximately 100-200 meters).

In addition, in addition to the power supply unit included in the project, it is proposed to place at least two more typical cafeterias: 1 - between the ethno-village and the amphitheater (open-air cinema); 2 - between the sports area and the rental place for sports equipment of the roller ski track.

When modeling the space, the implementation of the principle of accessibility and awareness of visitors is of great importance. This is primarily the placement of maps, diagrams and signs on orientation in the park, which should not only have an explanatory function, but also aesthetically please visitors, encourage them to visit these places.

The project requires special attention for people with limited mobility. Inclusive landscape design involves the placement of paths, steps, benches that will be comfortable for different age groups and people with limited mobility. These can be designed facilitating steps, seats, ramps, railings that will make the natural environment safe and comfortable (**Sinyavskaya, 2019, Morozova, Medvedeva & Dovbnya, 2024**).

Based on the interests of the safety of park visitors, the project should provide for facilities and a system for the timely prevention of anthropogenic threats (hooliganism, vandalism, failure to comply with fire safety rules, terrorist attacks). CCTV cameras, stationary devices (such as an "SOS panic button") should be installed on the park territory, it is necessary to resolve issues of park area security and access control, as well as lighting of the territory.

Lighting of park facilities performs a number of interrelated functions, including ensuring safety, comfort and aesthetics.

In general, the issues of attractiveness of public space are a combination of functional and aesthetic composition that creates an emotional release, encouraging people to visit the park area and receive a response in mental balance, physical health, satisfaction of interests, which is individual for each visitor.

Ethnic and decorative elements that combine the natural landscape and functional zones: art structures, photo zones, various locations with lighting, respond well to the emotional response of park visitors.

The requirements of modern times dictate the conditions, without fail, to provide visitors with access to innovative technologies: to place places for charging mobile phones and electric vehicles, to provide free Wi-Fi.

The real application of placemaking is not only the definition of desired processes, but also a significant step towards solving the problems of financing and promoting project ideas. In the modern world, the practice of participatory design is in great demand, both in the development of the concept of an object and its financing. For example, at the World Urban Parks Congress (Kazan, Russia, 2019, over 130 speakers and 1,500 delegates from all continents), the economic model of natural parks, tools and cases of their financing were discussed. “Different economic models of parks were considered: for example, La Mexicana in Mexico City exists 100% on private funds, and Bosque de Chapultepec in Mexico City (the largest in South America) is half made up of public funding, half by sponsors and income from events and souvenirs” (**Moldakhmetova, 2019**).

When city residents and wider communities are involved in the design of park space, then a common desire arises to make the facility a better and more exciting place for everyone. A sense of ownership, responsibility and participation in the creation of something new appears, and then - the management of these processes. During the discussion, motives for sponsors and ways to solve financial problems of construction are revealed. Financing a public space is a costly and lengthy process, but with great economic prospects. In order for the park to be in demand as a public space, it is necessary to constantly develop all recreational areas, hold cultural and mass, sports events, exhibitions, fairs, master classes and other events.

5 CONCLUSIONS

In conclusion, it should be noted that the study:

1. Identified typical problems of architectural and landscape design of parks of the post-Soviet period;

2. Identified and tested as the most effective approach to park renovation an integrated approach to the use of methods of environmental pre-project analysis, design by analogs and collage modeling, as well as placemaking and participation;

3. Developed the main architectural and planning directions for the renovation of parks of the post-Soviet period;

4. Substantiated the importance of the opinion of the public community in creating the concept of park space, in terms of implementing their vision of functionality, aesthetics and a scenario for subsequent development;

5. Proposed options for solving the problems of financing design solutions for the renovation of park space.

The practical value of the study is that, using the example of the developed integrated approach, an analysis of the master plan for the renovation of the Alash Arystary Park was carried out, focusing on the identified shortcomings and violations in the implementation of the existing project. In the course of the study, a number of proposals are made for adjustments to the master plan for the renovation of the park.

The significance of this study lies in the accessible presentation of the material, on the creation of a template module for preliminary project analysis of the renovation of a natural complex that meets the interests of visitors and determines the culture of the urban environment.

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RESEARCH ARTICLE

MODERN PRINCIPLES OF ORGANIZATION OF "OPEN SPACE" AREAS

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Abstract. *Due to modern requests and need to improve spatial characteristics, a popular form of a workspace called "open space" requires a detailed analysis and consideration of transformation ways using architectural and planning solutions. This article presents a brief overview and systematization of office "open spaces" and an experience in scientific and design developments, which allows to generalize the organization principles of a theoretical model of "open spaces". The research data consists of analytical and in-situation analysis based on materials collected by the authors. The article analyzes the advantages and disadvantages of this kind of organization of a workspace. The prospects for its development are related to creation of a working environment as a tool to ensure the effectiveness of a modern company. The increase of the intellectual part of work has led the search for ergonomic office spaces to optimal working conditions, and then to the formation of an office environment towards a qualitatively new organizational model – "work-home-leisure-food places". Research has shown that the transformation of open spaces nowadays is a result of objective factors of change in working relations. An integral characteristic of such a space currently is the requirement to workspaces for ergonomics, humanity, and facilitating of internal and external communication. The conducted research for improvement of open workspaces allows us to identify a number of necessary aspects, implementation of which guarantees a stable and demanded form of "open spaces" in the future. Recommendations are given taking into account different factors when organizing such spaces in the future.*

Keywords: *open space, office landscape, flexible planning, corporate organizational structure, architectural and compositional expressiveness, functional integration.*

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«OPEN SPACE» КЕҢІСТІГІН ҰЙЫМДАСТЫРУДЫҢ ЗАМАНАУИ ПРИНЦИПТЕРІ

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Аңдатпа. *"Open space" жұмыс кеңістігін ұйымдастырудың кең таралған түрі, заманауи сұраныстардың өзгеруіне байланысты және кеңістіктік сипаттамаларды жақсарту мақсатында сәулеттік-жоспарлау шешімдері арқылы трансформация мүмкіндіктерін егжей-тегжейлі талдауды және қарастыруды қажет етеді. Бұл жұмыста "open space" кеңсе кеңістігіне қысқаша шолу және жүйелеу, "open space" ашық кеңістіктердің теориялық моделін ұйымдастыру принциптерін жалпылауға мүмкіндік беретін ғылыми және жобалық әзірлемелер тәжірибесі ұсынылған. Бұл зерттеулер авторлар жинаған нақты материалға негізделген аналитикалық және табиғи талдаулардан тұрады. Мақалада мұндай кеңістікті ұйымдастырудың артықшылықтары мен кемшіліктері талданады. Олардың даму перспективалары қазіргі заманғы компания қызметінің тиімділігін қамтамасыз ететін құрал ретінде жұмыс ортасын құрумен байланысты. Еңбектің интеллектуалды компонентін кеңейту эргономикалық кеңсе кеңістігін іздеуді оңтайлы жұмыс жағдайына бағыттады, бұл кеңсе ортасының қалыптасуын сапалы жаңа ұйымдастырушылық модельге – "жұмыс-үй-демалыс-тамақтану" әкелді. Зерттеулер көрсеткендей, қазіргі уақытта болып жатқан ашық кеңістіктердің өзгеруі өндірістік қатынастардың өзгеруінің объективті факторларына байланысты. Қазіргі кезеңдегі мұндай ортаның ажырамас сипаттамасы кеңістіктің эргономикаға, адамгершілікке, ішкі және сыртқы коммуникацияны қамтамасыз етуге ұмтылуы болып табылады. Ашық жұмыс кеңістігін жақсартуды жалпылау бірқатар қажетті аспектілерді бөліп көрсетуге мүмкіндік береді, оларды жүзеге асыру "open space" тұрақты және сұранысқа ие формасына кепілдік береді. болашақта. Болашақта осындай кеңістіктерді ұйымдастыруда қосымша факторларды есепке алу бойынша ұсыныстар берілді.*

Түйін сөздер: *"open space "(open space)," кеңсе ландшафты", орналасу икемділігі, корпоративтік ұйымдық құрылым, сәулеттік-композициялық экспрессивтілік, функционалдық интеграция.*

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НАУЧНАЯ СТАТЬЯ

СОВРЕМЕННЫЕ ПРИНЦИПЫ ОРГАНИЗАЦИИ ПРОСТРАНСТВ «OPEN SPACE»

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Аннотация. *Широко распространенная форма организации рабочего пространства «open space», в связи с изменениями современных запросов и с целью улучшения пространственных характеристик, требует детального анализа и рассмотрения возможностей трансформации с помощью архитектурно-планировочных решений. В данной работе представлен краткий обзор и систематизация офисных пространств «open space», опыт научных и проектных разработок, позволяющий обобщить принципы организации теоретической модели открытых пространств «open space». Данные исследования складываются из аналитического и натурного анализа, базирующегося на фактическом материале, собранном авторами. В статье проанализированы преимущества и недостатки такой организации пространства. Расширение интеллектуальной составляющей труда направило поиски эргономичных офисных пространств к оптимальным условиям работы, что привело формирование офисной среды к качественно новой организационной модели – «работа-дом-досуг-общепит». Исследования показали, что трансформация открытых пространств, происходящая в данный момент времени обусловлена объективными факторами изменения производственных отношений. Неотъемлемой характеристикой такой среды на современном этапе является стремление пространства к эргономичности, гуманности, обеспечению внутренней и внешней коммуникации. Проведенные обобщения усовершенствования открытых рабочих пространств позволяют выделить ряд необходимых аспектов, реализация которых гарантирует устойчивую и востребованную форму «open space» в перспективе. Даны рекомендации по учету дополнительных факторов при организации подобных пространств в будущем.*

Ключевые слова: *«open space» (опен спейс), «офисный ландшафт», гибкость планировки, корпоративная организационная структура, архитектурно-композиционная выразительность, функциональная интеграция.*

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CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

АЛҒЫС / ҚАРЖЫЛАНДЫРУ КӨЗІ

Зерттеу жеке қаржыландыру көздерін пайдалана отырып жүргізілді.

МҮДДЕЛЕР ҚАҚТЫҒЫСЫ

Авторлар мүдделер қақтығысы жоқ деп мәлімдейді.

БЛАГОДАРНОСТИ / ИСТОЧНИК ФИНАНСИРОВАНИЯ

Исследование проводилось с использованием частных источников финансирования.

КОНФЛИКТ ИНТЕРЕСОВ

Авторы заявляют, что конфликта интересов нет.

1 INTRODUCTION

Many forms of social coexistence in our lives have a collective beginning, starting from childhood. Kindergarten, school, and university give us skills of social and collective activity and social coexistence. A person is a social being and can realize himself only in society because he or she needs to create and do something meaningful and useful for society. Therefore, when such a form of workplace organization as "open space" appeared, it seemed quite organic for teamwork and was perceived as a solution to many economic and social problems. But does such a space meet the needs of modern person? How does open space affect a person's psychological state, how does it allow us to preserve our individuality? These issues require detailed consideration.

Besides that, it should be taken into account that, in accordance with the principle of functional integration, in the modern world, the workflow is carried out not only in the workplace, but also in public places, cafes, transport, etc., which is possible due to the appropriate level of communication and technical means. Therefore, the office environment in progressive companies, at the present stage, is not created from the position of accommodating the maximum number of employees, but is focused on creating the most comfortable working conditions and combining various functional elements into a single interconnected organism.

2 LITERATURE REVIEW

The open organization of the workspace was analyzed theoretically and applied practically at the beginning of the 20th century by such architects as F.L. Wright – the Larkin building in New York. The building is described in the book "The Complete 1925 Wendingen Series" by F.L. Wright and F.A. Davis. (**Wright, & Davis, 1992**).

Another great architect, Ludwig Mies van der Rohe (Seagram office building in New York), contributed to the formation of the modern open space, which is described in the book "Building Seagram" by Phyllis Lambert (**Lambert, 2013**), as well as by the modern theorist A. Lange (**Lange, 2014**) - "The Dot-Com City: Silicon Valley Urbanism", etc.

The issues related to the new ideology of office space were considered in the theoretical works of D. Borodai, A. Borodai, & S. Borodai, (**Borodai, & Borodai, 2024**) D. Myerson (**Myerson, 2003**), D. Spath and R. Kern (**Spath, & Kern, 2003**) and other major architects.

Theoretical studies of the figurative, organizational, architectural and planning ideology of modern offices include the works of F. Duffy (**Duffy, 1997**), A. L. Gelfond (**Gelfond, 2003**).

At the same time, the complex issues of the formation of the architectural environment of "open spaces" insufficiently specified by national researchers. It is necessary to conduct an in-depth analysis of the architectural and planning organization of open office spaces as an architectural environment where intellectual activities take place and new forms of labor organization are continuously created, as well as to establish the principles of formation of modern highly efficient open office spaces associated with the values of society during the period of globalization.

3 MATERIALS AND METHODS

To achieve the purpose of the study, a two-stage method of information collection was applied:

- conducting an analysis of existing techniques for organizing workspace;

- collection of information through scientific sources, which are based on the study of all indirect and direct factors affecting the subject of research.

The study used the most characteristic planning techniques for organizing public space for each historical period, which had the greatest impact on the subsequent development of open space spaces, based on the characteristic methods of organizing social, business and labor activity in foreign countries of Europe and the United States.

Based on the analysis of specialized resources, including electronic archives and platforms, international peer-reviewed publications, the principal characteristics of the workplace organization were analyzed.

As a result, the analysis of existing methods of organizing open spaces, through a comprehensive study and systematization of current foreign design experience, a comparison of factors and an analytical review of reliable information, served as a theoretical basis for determining the ways of evolution and transformation of open spaces as a workplace organization in the era of the global process of increasing integration in the spheres of society.

4 RESULTS AND DISCUSSIONS

Transformation to organization of workplaces as open spaces began at the end of the XIX century. This method of organizing the workspace began to be used not only for economical reasons, but also to create a psychological atmosphere of transparency and strengthen control over employees. The first office of a such kind appeared a hundred years ago in the "Victorian" era, when cast-iron ceilings were used in buildings to create large indoor spaces (**Wright, & Davis, 1992**). **Figure 1** shows an example of the first open office spaces, implemented by architect F.L. Wright in 1906, during the industrial revolution, in which the first office premises for clerks appeared, primarily serving commercial and banking transactions. At that time, such an organization was considered the most productive. In the 50s of the last century, a more advanced form was used in Germany, which was called "office landscape" because its desks were arranged at various angles in a haphazard manner, forming work areas of different sizes and configurations (**Lange, 2014**).

By the 2000-s, open space had reached the peak of its popularity. Representatives of "communicative" professions work in a common open space more often than others. These are brokers (20%), advertising, marketing and logistics managers (10% each), design engineers, architects (14%), credit specialists (13%), call center operators and translators (15% each). And the methods of organizing such spaces, for various reasons, require changes and unification.

One of these reasons is the transfer of staff work to a hybrid mode - a combination of "remote" and office work, in which it is possible to fill open spaces not 100% and this largely negates the negative effects of working in such a space, and also gives "dynamism" to workplaces. According to the survey, the majority of employers (73%) consider it optimal to spend 2-3 days a week in the office. But for this, it is important that the office is located close to home (61%), the availability of infrastructure for leisure (11%) and modern design (9%).

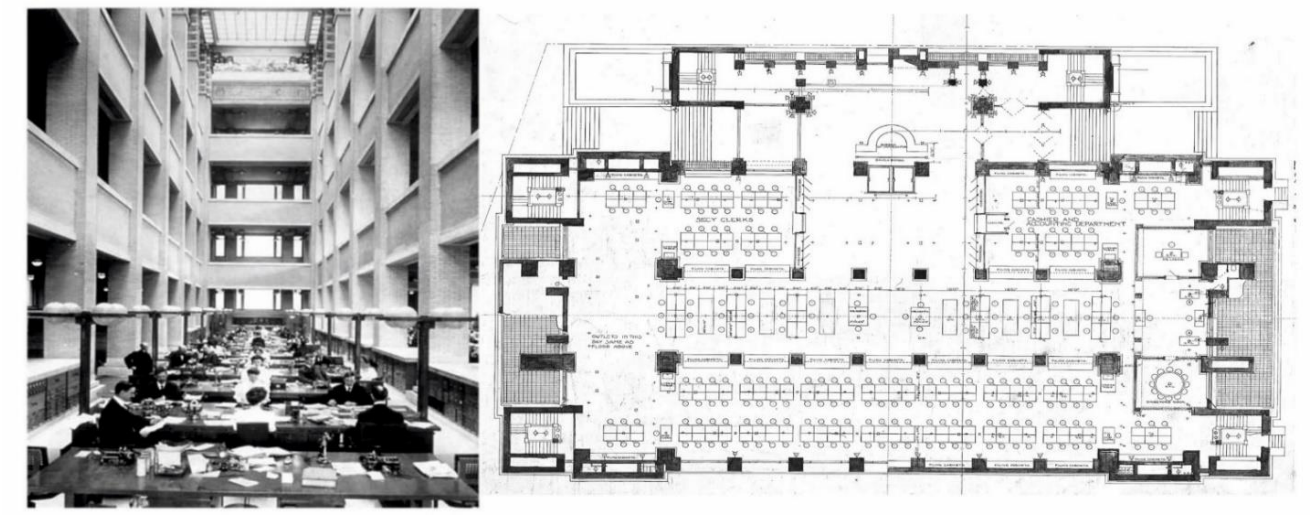

Figure 1 – F.L. Wright office space in the Larkin Building in New York in 1906. (URL: https://cyberpedia.su/3x86c.html)

To date, there are several types of organization of open space offices:

1. Team-oriented principle, it implies that workplaces are grouped into teams to hear and see each other.

2. Hybrid space represents workplaces as arranged using partitions, when employees seat at their desks without seeing each other.

3. Cluster workspace is a group of workplaces with low partitions, fenced off by high partitions from other work teams. **Figure 2** shows an example of the organization of such a space.

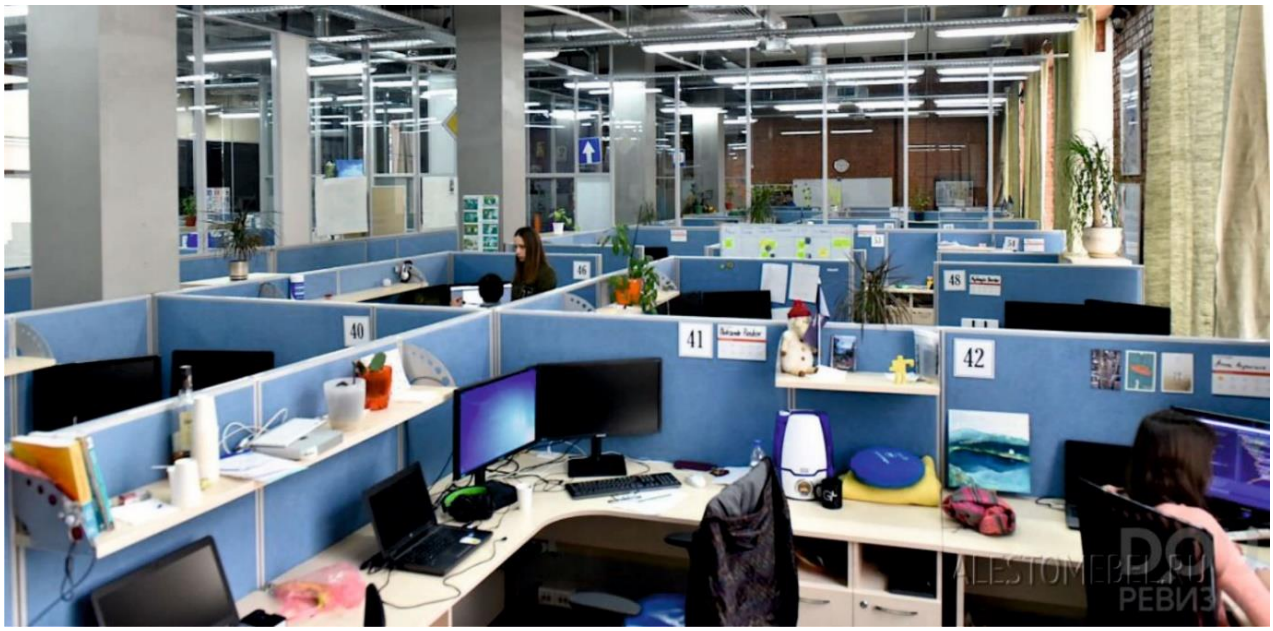

Figure 2 – The "open space" office of the 2000s. Cluster workspace: a group of workstations with low partitions. (URL: https://investment-estate.com/en/novosti/kak-vyglyadit-novyy-centralnyy-ofis-robert-bosch-ukraine-v-kieve-foto)

The use of the “open space” system for organizing the workspace offers both economic and social benefits because of the following reasons:

- saving space and materials due to the absence of the need for installing partitions and doors. Without these elements, engineering systems are more efficiently equipped, surface areas for partitions are not wasted;

- fast interaction of employees with each other. To solve operational issues, you do not need to go to the offices;

- simplified the process of monitoring the work of employees. Employees are at plain sight, therefore there is no opportunity to be distracted from work for a long time;

- democracy. Equality of all employees is ensured. Their statuses are equalized;

- maintaining the corporate spirit. A common space creates a unified working spirit.

The feeling of unity makes the team work more efficiently:

- simplification of document management. All documents are in the same space;

- effective use of office equipment.

But with the development of public relations, such a model of workplace organization is becoming morally obsolete. At the present stage, such spaces do not stand up to criticism in terms of primarily sanitary and epidemiological requirements (**Spath, & Kern, 2003**). **Figure 3** clearly shows all the negative aspects of the organization "open space" in the middle of the XIX century.

Figure 3 – The "open space" office in the middle.
The team-oriented principle of space organization because everyone sees and hears each other.
(URL: https://twitter.com/habr_popsci/status/821326209149714432)

In a selective survey of open space employees, the following indicators were obtained:

- 56% of employees claimed that they did not have enough personal space;
- 60% indicated an increased noise level;
- 55% were dissatisfied with the temperature regime of the room;
- 45% noted a lack of natural light.

Thus, the main and significant disadvantages of open spaces are:

- increased noise level;
- stress and reasons for conflict due to lack of personal space;
- insufficient sunlight in full-time working conditions;

- rapid spread of infectious diseases

The percentage of negative aspects was revealed through a survey of users of open spaces and is shown in **Figure 4**.

Figure 4 – Analysis of negative indicators of the open space workspace (authors' material).

Nowadays, the question arises of the need to reduce the negative impact of these factors and, thereby, increase the productivity of work in open spaces. The improvement of the open workspace at the present stage is more important than ever, it is necessary to revive such spaces for their demand in the future. To determine the prospects for development, it is necessary to identify the main characteristic structural elements of such an environment and the features of their interaction with each other.

The workspace itself also needs to be transformed. Firstly, the spatial organization must be clearly visible; secondly, ergonomics must be achievable without compromising the psychological comfort of employees; thirdly, the office must comply with modern standards of working spaces **(Bantserova O. L. & Kasimova A. R., 2023)**.

Based on the analysis of modern theoretical and practical developments, it is necessary to consider additional architectural and planning techniques and means for organizing open space that will enable a qualitative transformation of the workspace, specifically:

1. Due to the fact that each employee has their own individual needs, it is not recommended to standardize workplaces, but to use well-isolated modules.
2. Provide, properly position, and arrange nearby areas for eating, meeting rooms, and leisure spaces.
3. The meal room should be equipped with a kitchen, large, closed with doors for sound isolation and air-conditioning.
4. Avoidance of high partitions between workplaces. Such partitions visually reduce the space and work area of the employee, in the illusion of isolation, there is no silence.
5. Use of plants to create a friendly environment.
6. Control of area standard. At least 6.00 m2 is provided for organization of the workplace per one employee, while the spatial organization must be clearly visible, the office must comply with modern standards of air exchange, light and sound level.
7. Availability of office equipment for staff. In the printing area should be equipped with noise isolation.
8. Convenient routes to move between tables to the meeting and leisure areas, as well as to the exit.
9. The use of sound-absorbing floor covering.
10. Dividing the entire open office space into noisy and quiet zones.
11. Providing places of active recreation with board games and exercise equipment.
12. Toilet cabins should be completely enclosed, with maximum insulation. The office should be equipped with shower cabins.
13. Providing soundproof spaces for telephone conversations - "telephone booths".

The above techniques will determine the relevance and development of open spaces in the future. **Figure 5** shows some examples of the transformation of the modern workspace.

Figure 5 – Methods of organizing individual areas of the open space office nowadays.
(URL: http://milodamalo.ru/portfolio/tsup-avtovaz-open-space/)
(URL: https://www.floornature.com/top-offices-and-work-spaces-12800/)

The figure of the open space concept presented in **Figure 6** with a focus on future sustainability demonstrates the extent of the impact of using various techniques or design elements to achieve maximum psychological and physical comfort of employees and optimal business development.

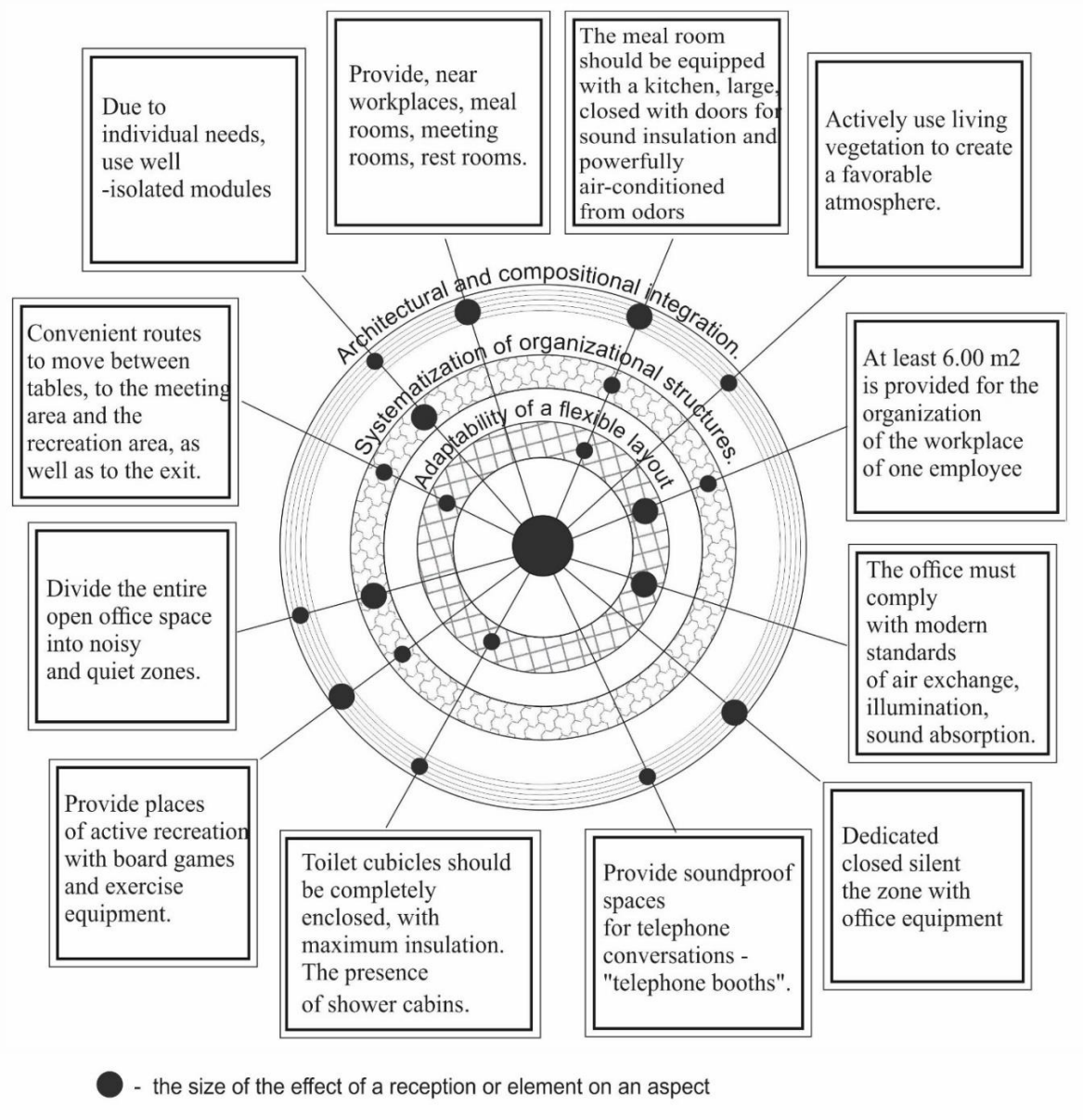

Figure 6 – The concept of organizing an open workplace [material by the authors]

5 CONCLUSIONS

To develop the communicative relevance of open spaces it is necessary to form a theoretical model of the organization of such a space through the definition of criteria for most optimal conditions. These criteria include:

1. *Adaptability of transformable design*. The ability to easily adapt the space to changing circumstances without stopping the work process. The workspace, as a systematically organized process, is constantly developing as well as the rules and conditions of labor organization.

2. *Systematization of the organizational structure.* The structure is responsible for two fundamental conditions, i.e. the division of labor into separate tasks and the coordination of actions to implement them. The success of the company is ensured by the interaction and exchange of information and knowledge among groups of employees and departments. A mandatory condition for the activity of a modern company is the close interaction of all its constituent elements, avoiding uncertainty and ensuring the diversity.

3. *Architectural and compositional integration*. Humanity, ensuring internal and external communication should become an integral characteristic of the communicative production environment at the present stage. In this case, "humanity" means creating the most comfortable

conditions for different groups of office workers, creating physical and psychological comfort for them. Such means include aesthetic comfort, which is achieved through such design techniques as well-chosen color, biophilic forms, and the scale of architectural and design elements to a person. The formation of an imaginative solution to the space should solve the tasks of self-identification of the company, informing, creating an aesthetic environment that initiates the work of an employee, perform a representative function, manifesting the status of the company in a material form.

The use of optimality criteria in organization of workplace will provide effective and sustainable forms leading to the decreasing the boundaries among work, home and leisure, which is a global trend in the modern world. Thus, the transformation of open spaces nowadays is due to objective changes in industrial relations.

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FORMATION AND DEVELOPMENT OF BUSINESS SPACE ARCHITECTURE

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Abstract. *The article is dedicated to studying the evolution of business spaces, from their origins in prehistoric times to the modern stage, where business centers have become an integral part of urban infrastructure. It analyzes the process of formation and development of multifunctional business spaces, which are a crucial element of public buildings. The article examines various typological features of business centers, including their functional zoning, planning, and compositional solutions. In a historical context, the transformation of business activity locations is traced: from chaotically organized markets and trade exchange points in ancient times to the antique agoras and Roman forums, where organized spaces for negotiations and product demonstrations already existed. The medieval period is characterized by the dominant role of monasteries and temples as centers of economic and banking activities. During the Renaissance, the first specialized buildings for conducting business appeared, such as the gallery in Florence, which became a prototype for modern office spaces. Particular attention is given to changes in workplace organization in the 19th–20th centuries: from compact offices to the concepts of "Bureau-landscape" and "Action office", as well as the emergence of cubicle systems. In the 21st century, business spaces have become flexible, adapting to digital technologies and new working methods, including coworking. An important focus of the study is the balance between individual and collective work, the impact of spatial organization on employee productivity, and issues of privacy and workplace comfort. The role of business spaces in creating an environment for communication, meetings, seminars, training sessions, and informal interactions is examined, as these aspects contribute to effective collaboration between employees and clients.*

Keywords: *business center, office building, banking, business space, multifunctional building, spatial organization.*

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БИЗНЕС-КЕҢІСТІКТЕР СӘУЛЕТІНІҢ ҚАЛЫПТАСУЫ МЕН ДАМУЫ

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Аңдатпа. *Бұл мақалада бизнес кеңістігінің эволюциясы қарастырылады, оның пайда болуынан бастап қазіргі кезеңге дейін, онда бизнес орталықтары қалалық инфрақұрылымның ажырамас бөлігіне айналды. Көпфункционалды іскерлік кеңістіктердің қалыптасу және даму үдерісі талданып, олардың қоғамдық ғимараттардың маңызды элементі ретіндегі рөлі зерттеледі. Мақалада бизнес орталықтарының түрлі типологиялық ерекшеліктері, оның ішінде функционалдық аймақтарға бөлу, жоспарлау және композициялық шешімдер қарастырылады. Тарихи контексте іскерлік белсенділік орындарының трансформациясы қарастырылады: ежелгі замандағы ретсіз ұйымдастырылған базарлар мен сауда алмасу нүктелерінен бастап, келіссөздер жүргізуге және өнім үлгілерін көрсетуге арналған ұйымдасқан алаңдары бар антикалық агорлар мен рим форумдарына дейін. Орта ғасырларда монастырлар мен ғибадатханалар экономикалық және банктік қызметтің орталықтары ретінде басым рөл атқарды. Қайта өрлеу дәуірінде бизнес жүргізуге арналған алғашқы арнайы ғимараттар пайда болды, мысалы, Флоренциядағы галерея, ол қазіргі кеңсе кеңістіктерінің прототипіне айналды. XIX–XX ғасырларда жұмыс орындарын ұйымдастырудағы өзгерістерге ерекше назар аударылады: шағын кеңселерден бастап «кеңсе ландшафты» және «әрекет кеңсесі» тұжырымдамаларына дейін, сондай-ақ кабиналық жүйелердің (кубикл) пайда болуы. XXI ғасырда бизнес кеңістіктер икемді болып, цифрлық технологиялар мен жаңа жұмыс тәсілдеріне, соның ішінде коворкингке бейімделе бастады. Зерттеудің маңызды бағыты – жеке және ұжымдық жұмыстың теңгерімі, кеңістікті ұйымдастырудың қызметкерлердің өнімділігіне әсері, құпиялылық пен жұмыс орнының жайлылығы мәселелері. Бизнес кеңістігінің коммуникация, кездесулер, семинарлар, тренингтер және бейресми қарым-қатынас алаңын қалыптастырудағы рөлі қарастырылады, бұл қызметкерлер мен клиенттердің тиімді өзара әрекеттесуіне ықпал етеді.*

Түйін сөздер: *бизнес-орталық, кеңсе ғимараты, банк мекемесі, бизнес-кеңістігі, көпфункционалды ғимарат, кеңістіктік ұйымдастыру.*

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ФОРМИРОВАНИЕ И РАЗВИТИЕ АРХИТЕКТУРЫ БИЗНЕС-ПРОСТРАНСТВ

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Аннотация. *Статья посвящена изучению эволюции бизнес-пространств, начиная с их зарождения в первобытные времена и до современного этапа, когда бизнес-центры стали неотъемлемой частью городской инфраструктуры. Приводится анализ процесса формирования и развития многофункциональных деловых пространств, которые являются важнейшим элементом общественных зданий. В статье рассматриваются различные типологические особенности бизнес-центров, включая их функциональное зонирование, планировочные и композиционные решения. В историческом контексте прослеживается трансформация мест деловой активности: от хаотично организованных рынков и точек обмена товаров в древности к античным агорам и римским форумам, где уже существовали организованные площадки для переговоров и демонстрации образцов продукции. Средневековый период характеризуется доминирующей ролью монастырей и храмов как центров экономической и банковской деятельности. В эпоху Возрождения появляются первые специализированные здания для ведения бизнеса, такие как галерея во Флоренции, которая стала прототипом современных офисных пространств. Особое внимание уделяется изменениям в организации рабочих мест в XIX–XX веках: от компактных офисов до концепций «бюро-ландшафта» и «офиса действий», а также появлению кабинных систем «кубикл». В XXI веке бизнес-пространства становятся гибкими, приспосабливаясь к цифровым технологиям и новым методам работы, включая коворкинг. Важной темой исследования является баланс между индивидуальной и коллективной работой, влияние пространственной организации на продуктивность сотрудников, вопросы конфиденциальности и комфорта рабочих мест. Рассматривается роль бизнес-пространств в формировании среды для коммуникации, проведения встреч, семинаров, тренингов, а также неформального общения, которая способствует эффективному взаимодействию сотрудников и клиентов.*

Ключевые слова: *бизнес-центр, офисное здание, банковское учреждение, бизнес-пространство, многофункциональное здание, пространственная организация.*

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CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

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Зерттеу жеке қаржыландыру көздерін пайдалана отырып жүргізілді.

МҮДДЕЛЕР ҚАҚТЫҒЫСЫ

Авторлар мүдделер қақтығысы жоқ деп мәлімдейді.

БЛАГОДАРНОСТИ/ИСТОЧНИК ФИНАНСИРОВАНИЯ

Исследование проводилось с использованием частных источников финансирования.

КОНФЛИКТ ИНТЕРЕСОВ

Авторы заявляют, что конфликта интересов нет.

1 INTRODUCTION

Business spaces have several characteristics that have been interpreted in different ways over the course of evolution.

Let us trace the process of forming a multifunctional building using the example of a business center as the most popular type of public building at the present time. The business center has a wide range of typological features: a varied set of functions, planning and compositional schemes. This is explained by the socio-cultural dynamics of business relations, which led to the complex evolution of the building on the basis of diverse historical prototypes (**Gelfond, 2006**).

Initially, business spaces appeared and sometimes were partially arranged in a somewhat chaotic manner. These were the meeting places for the exchange of the results of hunting, gathering, spoils of war and primitive production.

As the socio-cultural development progresses, business contacts become more frequent, and trade turnover grows. Places of commercial activity become more or less permanent geographically and in a concomitant manner are equipped with stationary or temporary open or semi-open pavilions of various sizes with places for placing goods and relatively convenient location of the participants in the transaction. At the same time, the sphere of related services (catering, sanitary services, entertainment, temporary accommodation and storage of goods) begins to develop nearby. As the direct commodity exchange is replaced by the “goods-money-goods” system, the need arises for the formation of points of exchange of volutes. Here, in a natural way, an organized space for the administration system appears. With the formation of cities, these spaces become part of the settlement.

The expansion of wholesale trade and intermediary activities has become in many ways the basis for the emergence of proper business spaces. Commercial activity has formed its own typology of markets and shops. When the possibilities of guaranteeing the results of the transaction developed, it became possible to negotiate a transaction outside the area where the entire mass of goods is located, using in some cases only its samples. As a result, the characteristic features of the spatial organization of the deal began to crystallize: a place for making a decision or conducting business communication, a place for registering a deal.

The development of economic, social, and technological activities in society directly influences the formation and evolution of business spaces. From the open market squares of ancient agoras and Roman forums of the 2nd century BC to modern office centers and flexible work zones, each historical change reflects the transformation of business methods, interactions, and management.

Over the centuries, business spaces have adapted to the changing demands of trade, finance, and governance. In the Middle Ages, monasteries and churches performed certain functions of banks and administrative centers, while the first exchanges and specialized trade spaces laid the foundation for the formation of modern office spaces. In subsequent eras, the strong development of the banking system, stock exchanges, and government administrative structures led to the emergence of specialized buildings as office spaces aimed at improving the efficiency of work processes.

Demonstrating new approaches to organizing business spaces, certain established concepts in the architectural and planning structure of modern office spaces have appeared, such as “Bureau-landscape”, “Action Office” and “Hot Desking”. The first concept is based on mobility and flexibility of space, created for the comfort of employees. Research into these trends and their historical origins not only allows us to define the principles of office environment development and their typological features but also to foresee future transformations of architectural spaces for business activities.

2 LITERATURE REVIEW

The results of the analysis and study of current trends in the development of the architecture of business centers in major cities of Kazakhstan are reflected in the works of Ignatyeva N.V. The main directions of the research include: analysis of the evolution of architectural solutions for business centers in major Kazakhstani cities; identification of modern trends in the design and construction of

business centers, taking into account international experience and local characteristics; investigation of the impact of economic, social, and cultural factors on the formation of the architectural appearance of business centers; development of recommendations for integrating business centers into the existing urban environment in accordance with the principles of sustainable development (**Ignatieva, 2010**).

The topic is also thoroughly presented in the work of Gelfond A.L., who considers the business center as a modern form of organizing public space, responding to new demands in economics, technology, and urban planning. The research focuses on: defining architectural and planning features of business centers; analyzing functional zoning; studying the transformation of public buildings; identifying the role of business centers in shaping the cityscape and public life; and developing architectural solutions that contribute to sustainable development and a comfortable urban environment (**Gelfond, 2002**).

A separate study by T.K. Uzakbayev (**Uzakbayev, 2023**) is devoted to identifying the evolution of the architecture of business centers — from early office buildings to modern multifunctional complexes — and integration trends related to changes in lifestyle, work formats, and user needs.

As for the detailing of specific aspects, general issues of urban placement are comprehensively addressed in the works of researchers such as Costa A.A., Lazareva M.V., and Korshunova N.N.

The parametric characteristics of this type of buildings are regulated by construction norms (**Online.zakon.kz, 2023**). Historical aspects of the issue and representative examples are presented in a number of encyclopedic and reference publications.

3 MATERIALS AND METHODS

A comprehensive methodological approach was applied in writing this scientific article, including theoretical and empirical methods of analysis. The main methods used in this research are as follows:

Historical-chronological method – This method allowed for the study of the stages of formation and evolution of business space architecture from the end of the II century BC to the present, helping to identify patterns influencing the formation of architectural business spaces.

Architectural-artistic analysis – Used to study the volumetric and spatial characteristics of business spaces.

Functional and typological analysis – Applied to classify types of business centers: traditional offices, coworking spaces, open spaces, and mixed-use formats.

Field survey and photo fixation – Conducted to collect visual material from real objects in the city of Almaty, including the external appearance and internal organization of modern spaces.

4 RESULTS AND DISCUSSION

In Antiquity, on agoras in Greece and later on forums in Rome, there were open spaces in the squares and in the surrounding galleries for communication between the parties to the transaction and the demonstration of samples of goods. From here originates and it is recorded from the end of the II century BC its activity. Small semi-open or closed rooms for consultation and decision-making were relatively visually isolated. They were often located in temples.

In the early stages of the culture of the Western European Middle Ages, monasteries and temples were powerful business and banking centers. They acted as economic and financial “dictators”, performing managerial, clerical and banking functions (**Gelfond, 2006**).

Medieval European monasteries had areas dedicated to writing and copying manuscripts, called scriptoria, which were the medieval prototype of the modern study. Separate alcoves, closed off by curtains, were used to increase concentration and productivity while working. An example of a painting “St. Augustine in His Study”, depicts St. Augustine working in a secluded room by Italian artist Sandro Botticelli, circa 1490-1494 (**Figure 1**).

Isolated rooms with limited access were places for storing documentation for the administration of commercial activities. Subsequently, as both commercial and regulatory documentation accumulated, they separated into a separate typological group, from which, being supplemented by works of a scientific, cognitive and cultural and educational nature, libraries and archives were formed.

The Central and Northern European Middle Ages provide examples of the already clear differentiation of certain types of business spaces. At the same time, markets with small-piece trade remain on the squares. Important for the spatial organization was the massive appearance on the market since the 12th century of bills, which made it possible to receive goods not directly, but at a later date convenient for settlements were carried out mainly by promissory notes, which were exchanged for money at the end of trading. It also influenced the specifics of the organization of the business space.

(a) (b)

Figure 1 – Medieval prototype of business space: a) Group business space in a multifunctional room of the European Middle Ages (**History-Thema, n.d.**); b) Individual business space in a multifunctional room of the European Middle Ages (**Botticelli, ca.1495**).

For small and medium-sized businesses, office work was done at home, with many store owners living above their stores and hiring clerks to help with bills, paperwork, and daily household chores.

Gradually, the main part of state and municipal administration of business activity merges with other governing bodies and, in order to optimize these services in space, office buildings are formed that have become an independent typological unit. A typical example is the Gallery of Offices, Florence (1581, architect G. Wazzari), intended for the Medici Bank and became a kind of prototype for corporate headquarters. Changes from the stores as the turnover increased and the need to fix each exchange operation appeared such a common typological unit as banks.

Typological development of buildings is directly related to the history of the development of banking. It is known that banks arose as a result of monetary and commodity relations in antiquity. Already in the ancient and feudal world, the bank acts as an intermediary in payments, performs the functions of exchanging money (**Gelfond, 2006**).

Trade in specially designated places on the streets or in catering establishments moved to adapted and later purpose-built buildings. For example, the Amsterdam Stock Exchange began operating in 1602, in a separate building. The growth of trade operations led to the need for a new building. It was here that the main implementation of goods was introduced. This made it possible not to demonstrate the goods themselves in the process of direct trade or resale, which influenced the organization of the business space. As a result, the premises for the actual trading were divided with the areas for negotiations and the premises for the administration of commercial activities.

Based on the above studies of the development of the business space, it is possible to determine the following individual parameters, which together determine the individual characteristics of each of them: degree of organization (organized, semi-organized, spontaneous); degree of commodity

specialization (specialized, mixed, non-specialized); degree of openness (open, semi-open, closed); degree of mobility (fixed, moving, non-fixed); degree of temporality (short-term, long-term, permanent); degree of transformability (transformable, partially transformable, non-transformable); degree of expandability (expanding, narrowing, pulsating); degree of individuality (individual, group, mass); degree of accessibility (public, limited, corporate); degree of manageability (externally administered, internally administered, externally and internally administered) (**Figure 2**).

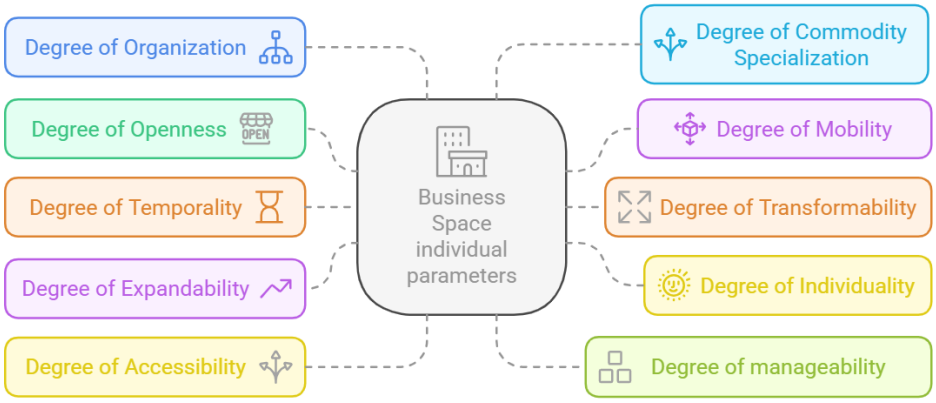


Figure 2 – Business spaces individual parameters (author's material)

The developing system required a kind of organization of jobs. On the one hand, decision-makers need isolated spaces that exclude the possibility of their accidental distraction by other employees, which determined the appearance of individual offices. On the other hand, for the current work, technologically providing for direct contact and control over the performance of official duties, common premises are required, corresponding to the structure of the office. At the same time, employees performing control functions could be located in the same room, maintaining full visual contact with the controlled group. As the engineering systems for artificial lighting and ventilation improved, common office spaces became larger and larger.

The use of sound-absorbing ceiling and partition panels has become essential for the normal functioning of such premises. For the convenience of those working in adjoining rooms, there was a kitchen for warming up a semi-finished product or a small dining room. Called the Taylorism at the turn of the last century and before last, this system of organization existed with minor changes until the middle of the twentieth century.

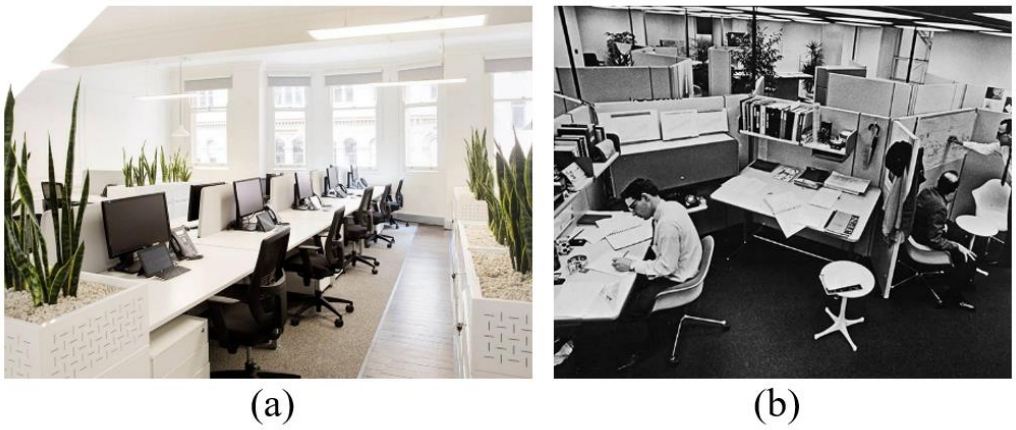


Figure 3 – General business spaces of the XX-XXI centuries: a) "Bureau-landscape" 1950 (**Everprof, 2024**). b) "Action office" 1963 (**IB Group, 2022**).

In the 1950s, the German bureau-landscape system began to spread, with a less cramped, natural placement of employees. Workplaces in this system are located in groups of various sizes, and low

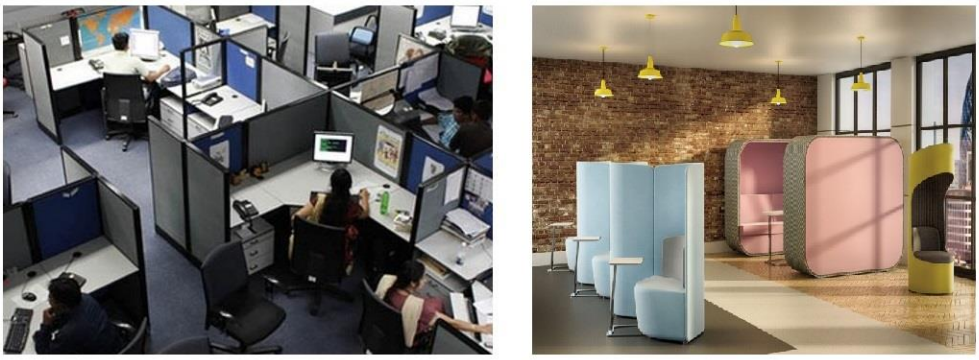
partitions between adjacent divisions are made of various indoor plants. An evolution of this system was the “Action office”, which introduced the concept of flexible, semi-enclosed workspaces that allowed office space to be personalized and often changed to suit the needs of the company and its employees. The rationale for this system was the understanding that workers needed large dedicated spaces for various types of work - space to record and make calls (**Figure 3**).

Over time, the concept of an “Office of action” evolved to such an extent that each of the employees had their own high, three-way vertical division that defined their individual space, and which they could autonomously personalize.

This concept, invented by R. Propst “Cubicle”, has been widespread since the 1980s. This is a massively cost-reduced and standardized version of the “Office of Action” concept, featuring cheap and uniform fixed partitions – visually resembling a box, with minimal space and maximum employee density. Businesses adopted this concept to save on rent and furnishings, and it became a symbol of corporate culture in the second half of the 20th century, especially in the United States. Even with such individualized spaces, the main drawbacks related to acoustic discomfort remained.

A proposed solution was a new concept called the “Cocoon”, invented by Finnish designer Eero Aarnio. The “Cocoon” concept is an approach to office space organization that places special emphasis on employee privacy, comfort, and psychological safety.

The concept allows for the creation of isolated zones within office spaces that resemble a cocoon in shape and feel, enabling users to focus on their work while reducing stress and distractions. The main features of the “Cocoon” concept include: tall enclosing elements that provide visual and acoustic isolation; soft textures and materials that enhance coziness; a human-centered design incorporating biophilic elements (plants, natural colors, organic forms); and flexible use—these zones are suitable for both individual work and informal communication. This approach has become especially relevant in the post-pandemic period, as the demand for comfortable and adaptable workspaces has increased (**Figure 4**).



(a) (b)

Figure 4 – General business spaces of the XX-XXI centuries: a) Paired “Cubicle” in the common space (**LAS, 2015**). b) The Cocoon Concept (**Collaborative Office Interiors, 2025**).

As technology advances workers have become more mobile, they can work anywhere: it has become the norm to see people working in cafes, coffee shops and homes as companies have begun to adopt these new ways of working. As mobility became the norm, office design began to embrace the “Hot Desking” boom, with no space allocated to staff and employees choosing an empty space to work. This is due to the increase in the number of freelancers, the demand for part-time work, flexible office space and creative collaboration.

As the development progresses, the individual cabinet acquires some transformations. It offers both the opportunity for individual work and the opportunity to communicate with clients and colleagues. With a certain level of responsibility, meeting places are organized in or near the offices. The equipment, furnishings, saturation of the office with means of communication and information storage are changing. For the top level, lounges with bathrooms, mini-kitchens, canteens, wardrobes

are added to the office. An additional entrance and exit are organized, bypassing the areas for placing ordinary employees. However, the basic principles presented in the office - the emphasis on privacy, focus, and individuality in the workplace - is returning to the forefront and playing an increasingly important role as decisions critical to successful business are made in a comfortable environment (**Uzakbayev, 2023**).

Business spaces are also important for holding meetings of employees of various levels, individual or group communication with clients, seminars and trainings. To create an atmosphere of informal communication with clients, "coffee shops" appear (coffee + office), which allow discussing positions in the process of eating.

Remote work could lead to a decrease in the value of office real estate by 2030, according to analysts from the consulting firm McKinsey. Their data shows that only 37% of employees worldwide currently continue to work offline. As a result, the demand for office space has significantly declined. The study suggests that this trend is likely to persist in the coming years. Experts believe that this figure may have a negative impact on the global economy, potentially leading to a loss of investments, a drop in real estate values, and a reduction in jobs (**24.kz, 2023**).

This analysis suggests that we are currently undergoing a transitional period in the organization of work processes. Employees are gradually returning to office spaces, but not in full capacity. The pandemic period required a special approach to the use of workspaces.

The development of technology has provided humanity with the ability to work anytime and from anywhere. By the end of 2019, flexible approaches to workspace organization had become widespread and were increasingly applied in office design.

Thus, the concept of hybrid workspaces has gained popularity in recent years, especially as many companies began shifting employees to remote work.

Accordingly, such changes impact office spaces, prompting architects to adopt hybrid systems that can be adapted for various types of work and employee needs, combining elements of both individual work and collaborative activities. These zones are designed with flexibility in mind, allowing for easy modification of their functions based on tasks. The main features of hybrid zones are as follows: *Focus Zones; Collaboration Zones; Meeting Rooms; Lounge and Social Areas; Flexible Workstations; Ancillary Spaces* (**Figure 5**).

Figure 5 – The main features of hybrid zones (author's material).

Considering the above-mentioned aspects, the implementation of the hybrid workspace concept is proposed using the example of the Capital Tower business center (**Table 1**) (**Figure 6**). The average values, based on popular recommendations for hybrid office spaces, may vary depending on the specific needs of different organizations and their requirements. However, in general, hybrid offices typically follow these proportions: Focus Zones – 20%; Collaboration Zones – 25%; Lounge and Social Areas – 17%; Meeting Rooms – 13%; Flexible Workstations – 15%; Ancillary Spaces – 10%.

Table 1
Spatial distribution for a 460 m² office [author's material]

№	Zone	Area (m²)	Function
1	Focus Zones	92	Individual work, concentration
2	Collaboration Zones	115	Team tasks, brainstorming
3	Meeting Rooms	60	Offline/online meetings, Zoom
4	Flexible Workstations	69	Universal workspaces
5	Lounge & Social Areas	78	Informal communication, relaxation, coffee breaks, sleep, mini-fitness, recovery
6	Ancillary Spaces	46	Kitchen, printing area, wardrobe, storage
	Total:	460 m²	

The layout of hybrid zones should be adaptive, multifunctional, and foster improved interaction between employees. It is crucial that the space maintains a balance between work areas, relaxation and creativity zones, while also offering flexibility to alter functions based on the needs of the company and its employees.

Figure 6 – The concept of hybrid workspaces is illustrated through the layout of Office No. 4 with an area of 460 m² in the Capital Tower business center, Almaty (author's material).

This concept integrates all the elements of a traditional office environment while allowing employees to perform their duties both from the office and remotely. Such an approach is characterized by a high degree of flexibility and adaptability in work organization, enabling effective collaboration among employees regardless of their location.

5 CONCLUSIONS

1) Business spaces are modern multifunctional business centers that trace their origins back to antiquity, where agoras and forums served not only as places of trade but also as venues for negotiations, product demonstrations, and decision-making.

2) The lowest level of organization was characteristic of spontaneously emerging business spaces during the primitive communal era. Antiquity demonstrates a certain degree of order in business processes, while the Middle Ages saw the formation of a developed system of internal and external administration. During this period, the foundation was also laid for working not with entire batches of goods, but with samples—an innovation that changed the structure of business spaces.

3) Throughout these eras, various spaces such as temples, town halls, and establishments of public catering and trade were adapted for business activities.

4) Business spaces have the following individual parameters, which together determine the individual characteristics of each of them: degree of organization (organized, semi-organized, spontaneous); degree of commodity specialization (specialized, mixed, non-specialized); degree of

openness (open, semi-open, closed); degree of mobility (fixed, moving, non-fixed); degree of temporality (short-term, long-term, permanent); degree of transformability (transformable, partially transformable, non-transformable); degree of expandability (expanding, narrowing, pulsating); degree of individuality (individual, group, mass); degree of accessibility (public, limited, corporate); degree of manageability (externally administered, internally administered, externally and internally administered).

5) The set of parameters defining business spaces has been continuously refined throughout their development, accompanied by improvements in the conditions for conducting trade and intermediary activities in terms of cultural and everyday comfort, external and internal administration, informational and consultative support, legal and financial services, operational security, and accessibility.

6) The emergence of the concepts of the "Action Office", "Cubicles", and "Bureau-landscape" reflected an attempt to balance individuality, efficiency, and team collaboration among employees. Modern concepts, such as the "Cocoon" and "Hybrid offices", focus on comfort, flexibility, and the psychological well-being of employees, taking into account the demands of the post-pandemic reality.

7) The future of office spaces lies in hybrid formats that combine remote and in-person work, becoming the dominant model of work organization. This requires architects and designers to create spaces that can quickly adapt to changing conditions.

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RESEARCH ARTICLE

3D PRINTING OF FINE-GRAINED CONCRETE WITH NANO-BLEND

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Abstract. *The integration of modern computer technologies into the construction industry is transforming design and building processes, offering professionals numerous advantages. One of the most significant advancements is the adoption of virtual modeling tools, which enhance design accuracy, improve project quality, and reduce implementation time. These technologies also optimize material costs, making construction more efficient and cost-effective. A major milestone in this digital transformation is the widespread use of Building Information Modeling (BIM) technologies, such as Revit and Archicad. These programs create a unified software environment that streamlines project management across all stages, from initial design to construction and operation. Additionally, they enable the development of complex architectural forms through 3D printing, further expanding the potential of modern construction methods. The success of 3D printing in construction depends heavily on advanced materials, particularly fine-grained concrete with inorganic binders. While these materials enhance durability and structural integrity, their development remains a challenge due to strict technical requirements. Overcoming these challenges requires a scientifically grounded approach to optimizing material composition and ensuring seamless integration into additive manufacturing processes. In conclusion, the fusion of digital tools with construction methodologies significantly improves efficiency, precision, and sustainability. These innovations not only advance the design and building processes but also pave the way for the successful realization of complex and economically viable projects, shaping the future of the construction industry.*

Keywords: *nano silicon, fine-grained concrete, 3D printer, strength, modified additives, hydro silicates, water-cement ratio*.

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НАНО ҚОСПАСЫ БАР ҰСАҚ ТҮЙІРШІКТІ БЕТОНДЫ 3D-да БАСЫП ШЫҒАРУ

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Аңдатпа. *Қазіргі заманғы компьютерлік технологиялардың құрылыс саласына енгізілуі жобалау және құрылыс үдерістерін түбегейлі өзгертіп, мамандарға көптеген артықшылықтар ұсынып отыр. Ең маңызды жаңалықтардың бірі – жобалау дәлдігін арттырып, жоба сапасын жақсартатын және іске асыру уақыты мен шығындарын азайтатын виртуалды модельдеу құралдарын пайдалану. Бұл технологиялар сондай-ақ материалдық шығындарды оңтайландырып, құрылысты анағұрлым тиімді әрі үнемді етеді. Цифрлық трансформациядағы маңызды кезеңдердің бірі – Building Information Modeling (BIM) технологияларының, атап айтқанда Revit пен Archicad секілді бағдарламалардың кеңінен қолданылуы. Бұл бағдарламалар жобалаудан бастап құрылыс пен пайдалануға беру кезеңдеріне дейінгі барлық үдерісті біріктіретін біртұтас бағдарламалық орта қалыптастырады. Сонымен қатар, олар 3D басып шығару арқылы күрделі сәулеттік формаларды әзірлеуге мүмкіндік беріп, қазіргі құрылыс әдістерінің мүмкіндіктерін кеңейтеді. Құрылыста 3D басып шығарудың табысты болуы негізінен бейорганикалық байланыстырғыштары бар ұсақ түйіршікті бетон секілді жетілдірілген материалдарға байланысты. Бұл материалдар беріктік пен құрылымдық тұтастықты арттырады, алайда олардың дамуы қатаң техникалық талаптарға байланысты күрделі міндет болып қала береді. Бұл мәселелерді шешу үшін материал құрамын ғылыми негізде оңтайландырып, оларды аддитивті өндіріс үдерістеріне үйлесімді енгізу қажет. Қорытындылай келе, цифрлық құралдар мен құрылыс әдістерінің үйлесімі тиімділік, дәлдік және тұрақтылық деңгейін айтарлықтай арттырады. Бұл жаңалықтар жобалау мен құрылыс үдерістерін жетілдіріп қана қоймай, сонымен қатар күрделі әрі экономикалық тұрғыдан тиімді жобаларды табысты жүзеге асыруға жол ашып, құрылыс саласының болашағын қалыптастырады.*

Түйін сөздер: *нано кремний, түйіршікті бетон, 3D принтер, беріктілік, модификациялық қоспалар, гидросиликаттар, су-цемент қатынасы*.

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3D-ПЕЧАТЬ МЕЛКОЗЕРНИСТОГО БЕТОНА С НАНО-СМЕСЬЮ

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Аннотация. *Внедрение современных компьютерных технологий в строительную отрасль трансформирует процессы проектирования и строительства, предоставляя специалистам многочисленные преимущества. Одним из наиболее значимых достижений является применение инструментов виртуального моделирования, которые повышают точность проектирования, улучшают качество проектов и сокращают время их реализации. Эти технологии также оптимизируют затраты на материалы, делая строительство более эффективным и экономичным. Важным этапом цифровой трансформации стало широкое использование технологий информационного моделирования зданий (BIM), таких как Revit и Archicad. Эти программы создают единую программную среду, которая упрощает управление проектом на всех этапах – от первоначального проектирования до строительства и эксплуатации. Кроме того, они позволяют разрабатывать сложные архитектурные формы с помощью 3D-печати, расширяя возможности современных строительных методов. Успех 3D-печати в строительстве во многом зависит от передовых материалов, особенно от мелкозернистого бетона с неорганическими вяжущими. Несмотря на то, что эти материалы повышают долговечность и структурную целостность, их разработка остается сложной задачей из-за строгих технических требований. Для преодоления этих трудностей необходим научно обоснованный подход к оптимизации состава материалов и обеспечению их бесшовной интеграции в аддитивные производственные процессы. В заключение, интеграция цифровых инструментов с методами строительства значительно повышает эффективность, точность и устойчивость. Эти инновации не только способствуют развитию процессов проектирования и строительства, но и прокладывают путь для успешной реализации сложных и экономически выгодных проектов, формируя будущее строительной отрасли.*

Ключевые слова: *нано кремний, мелкозернистый бетон, 3D принтер, прочность, модифицированные добавки, гидросиликаты, водоцементное отношение.*

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CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

АЛҒЫС / ҚАРЖЫЛАНДЫРУ КӨЗІ

Зерттеу жеке қаржыландыру көздерін пайдалана отырып жүргізілді.

МҮДДЕЛЕР ҚАҚТЫҒЫСЫ

Авторлар мүдделер қақтығысы жоқ деп мәлімдейді.

БЛАГОДАРНОСТИ/ИСТОЧНИК ФИНАНСИРОВАНИЯ

Исследование проводилось с использованием частных источников финансирования.

КОНФЛИКТ ИНТЕРЕСОВ

Авторы заявляют, что конфликта интересов нет.

1 INTRODUCTION

The construction industry is actively adopting BIM technologies and software like Revit and Archicad, enabling the design and construction of buildings through 3D printing. For creating materials for construction objects, a variety of materials based on inorganic binders with specific properties are used, depending on the product's purpose and the chosen 3D printing method.

This study focuses on modifying fine-grained concrete using nano-silica. The introduction of chemical additives makes it possible to produce high-strength concrete with rapid hardening properties. To enhance and accelerate strength development, the optimal dosage of the additive was determined. Adding nano-silica resulted in a strength increase of 1.4 times (or 76.3%) within one day, 76.3% within three days, 66.2% within seven days, and 44.0% within 28 days. The results also demonstrated a significantly accelerated strength gain.

The key characteristic of concrete is its compressive strength. To ensure rapid and high-quality construction, it is recommended to use high-strength concrete that gains substantial strength during the initial curing period. This can be achieved by incorporating nano-silica additives **(Zolotaryeva, S. V., 2016)**.

Despite the globally proven efficiency of active mineral additives, their usage in Kazakhstan remains limited. The main reasons include their dusty, hygroscopic, and lightweight nature, making them less suitable for some applications. Such materials tend to clog technological equipment and cement delivery systems. In specific cases, the consumption of such fillers can reach 200–250 kg per cubic meter of concrete, requiring additional cement silos at concrete plants for storage. Moreover, the low bulk density of mineral fillers, often as low as 150 kg/m³, further increases costs **(Baigarina, A., Shehab, E., & Ali, M. H., 2023).**

The effectiveness of active fillers is often assessed by their impact on strength properties. When a specific amount of cement is replaced by an equivalent amount of active filler, the resulting increase in concrete strength serves as a performance indicator. However, the benefits of nano-silica extend beyond strength improvement. Nano-silica acts as a critical component in high-strength, corrosion-resistant, and frost-resistant concrete.

Nano-silica particles are up to 100 times smaller than cement particles and exhibit high pozzolanic reactivity due to their large surface area and high silicon dioxide content. A standard dose of 40 kg of nano-silica provides a surface area sufficient to react with calcium hydroxide released during cement hydration. This early pozzolanic activity sets nano-silica apart from other additives. In concrete containing nano-silica, the porous structure shows a marked reduction in capillary pores and an increase in fine gel pores. The amount of chemically bound water and the degree of Portland cement hydration indicate that nano-silica accelerates hydration significantly during the initial seven days. At a constant water-cement ratio, concrete with nano-silica achieves a hydration level at seven days comparable to that of ordinary cement at 28 days. This acceleration results in a twofold increase in concrete strength under both normal humidity and elevated temperatures of 60°C **(Mustafin, N. Sh., & Baryshnikov, A. A., 2015), (Rudyak, K. A., & Chernychev, Y. O.2016).**

The improved hydration of calcium silicates and the reduction of capillary pores provide two key benefits for nano-silica-modified concrete: high strength and low permeability. These enhancements make the concrete highly resistant to physical (wear, erosion, and impact) and chemical (water, sulfates, chlorides, organic substances, and acids) effects.

Studies of concrete structures containing nano-silica have shown that such materials maintain durability for up to 10 years. High-quality concretes with nano-silica additives demonstrate superior resistance to carbonation and chloride penetration from seawater compared to ordinary Portland cement concretes with equivalent strength. Under proper conditions, nano-silica-modified concrete offers excellent protection for steel reinforcement, comparable to that provided by ordinary Portland cement concretes of the same strength class **(Ilyina, L. V., & Zavadskaya, L. V.,2018), (Inozemtsev, A. S., Korolev, E. V., & Zhyong, Thanh Kui. 2018).**

2 LITERATURE REVIEW

Considering the results of various experiments by different researchers, it can be noted that the specific surface area of SiO_2 nanoparticles (S = 50 to 450–900 m^2/g) is a critical factor in improving the mechanical performance of concrete. This improvement is achieved by activating the hydration reaction of calcium silicates, forming C-S-H hydrates, and modifying the nanostructure of the C-S-H gel.

The use of nano-silica provides several benefits, including:

- Enhancing resistance to abrasion;
- Reducing cement consumption;
- Increasing the strength of concrete, particularly in fine-grained mixtures;
- Improving early strength under normal curing conditions (25–40 MPa within the first 24 hours);
- Producing highly workable, non-segregating concrete mixtures with a slump of 20–24 cm;
- Increasing corrosion resistance.

The addition of nano-silica reduces water permeability by 50%, doubles sulfate resistance, and increases frost resistance to F500. As research indicates (**Ibragimov, R. A., & Izotov, V. S. 2014**), the objective of this study is to analyze the effect of nano-silica on the strength characteristics of fine-grained concrete and to determine its optimal dosage.

In research on improving concrete strength through nano-silica modification, Portland cement of the CEM I 42.5 H grade, produced by the Shymkent Cement Plant, was used as the binder. As reported in previous studies (**Krasinikova & Ilyina, 2011,2016**), the mineralogical composition of the cement (by mass, %) was as follows: C_3S – 60.0; C_2S – 15.5; C_3A – 8.4; C_4AF – 11.3; free CaO – 0.50. The study used washed quartz sand from the Kapshagay quarry. According to research findings (**Krasinikova et al., 2016**), the sand complied with GOST 8736-2014 for construction sands, with a natural moisture content of 6–7%, a bulk density of 1450 kg/m^3, a true density of 2600 kg/m^3, a fineness modulus of 2.9, and impurity content of 0.5%.

Nano-silica was used as a modifying additive and met the requirements of technical specifications. As specified by the manufacturer **(Krasinikova, 2016),** the average particle size of the initial nano-silica particles was 12 nm, with a pH of 3.6–4.3. Nano-silica is a bluish-white material with a specific surface area of 200 m^2/g. Its chemical composition (by mass, %) is as follows: SiO_2 – 99.5; Al_2O_3 – 0.05; Fe_2O_3 – 0.001; TiO_2 – 0.01.

Master Rheobuild 1000 superplasticizer was used as a plasticizing agent, with a density of 1095 kg/m^3 and a solid content of 20% by mass. As noted in studies **(Ilyina et al., 2011),** the superplasticizer was added at a dosage of 0.5% by cement weight.

3 MATERIALS AND METHODS

To determine the characteristics of a fine-grained concrete mixture and fine-grained concrete, a mixture was prepared consisting of Portland cement, including 60 kg of cement, 1340 kg of sand, and 260 liters of water. Nano-silica powder was added to the water solution, and its uniform distribution was achieved through ultrasonic treatment. The resulting solution was added to the dry sand and cement mixture. The cement-sand solution was prepared using mechanical mixing for 60–90 seconds. From the obtained mixture, 40x40x160 mm column specimens were formed, which were cured under normal conditions for 3, 7, and 29 days.

Micro-silica, reacting a second time with calcium hydroxide, helps reduce the capillary porosity of cement paste by densifying the structure and sealing the pores of low-base calcium hydrosilicates. Detailed studies on the kinetics of strength development and the porosity characteristics of cement paste show that the introduction of micro-silica and superplasticizers into concrete significantly reduces the number of all types of pores compared to unmodified cement paste. The effectiveness of micro-silica is associated with the rate of pH reduction in the hardening system environment, which

accelerates the main hydration reactions of cement **(Potapov, V. V., & Gorev, D. S. 2018)**. As shown in **Figure 1**, the microstructure of the cement paste becomes denser after the addition of microsilica.

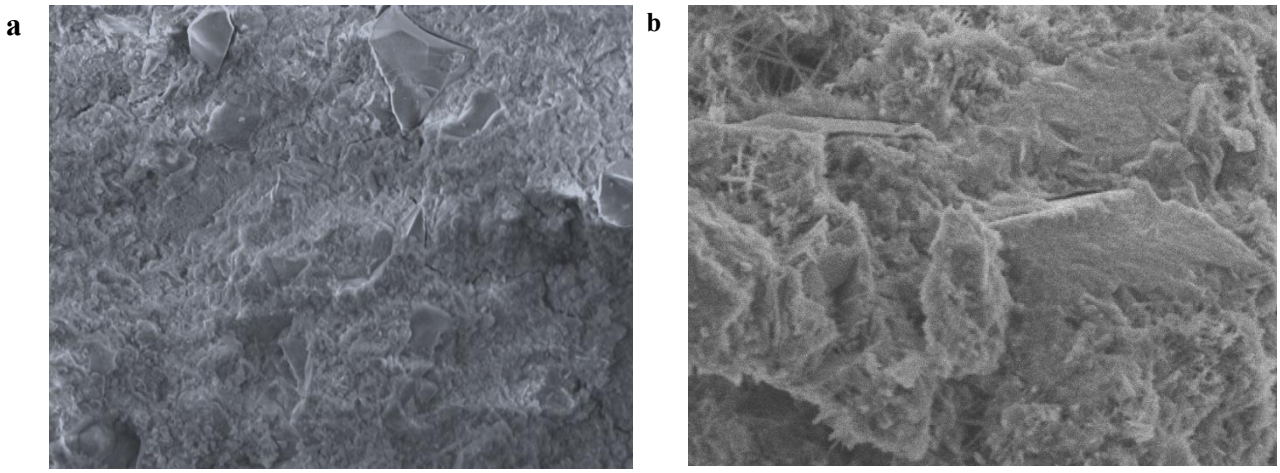

Figure 1 – SEM images of the cement paste microstructure:**a** – control sample without microsilica; **b** – sample with microsilica additive.

By reducing the concentration of calcium ions in the liquid phase of the cement paste, micro-silica in the mixture contributes to the formation of gel-like low-base calcium hydrosilicates in hydrated phases. This results in a simultaneous increase in gel pores and a decrease in the capillary porosity of the cement paste. It has been determined that micro-silica additives allow for obtaining high-strength dense cement paste. Furthermore, the correspondence between the phase composition and structure of the cement paste after heat-moisture treatment and normal curing enables the production of high-quality concrete with an accelerated strength gain rate under normal conditions. Micro-silica significantly increases the hydration degree of alite in the early stages.

Concrete modified with micro-silica is characterized by reduced water permeability, increased resistance to alkali, sulfate, and frost aggression. In studies of concrete degradation mechanisms, the primary durability factor is often considered to be the presence of open capillary pores that are easily filled with liquid phases during freezing, leading to hydraulic and crystallization pressure buildup. This causes stress in the concrete, with stress concentration occurring at structural defect sites, leading to local damage—crack formation and propagation accompanied by residual strain growth. To minimize frost damage, it is recommended to reduce open porosity (by densifying the concrete mixture and optimizing curing conditions with a lower water-to-cement ratio (W/C)) and to ensure reserve porosity for compressible pore water by using air-entraining additives, which reduce hydraulic pressure.

Experience shows that air entrainment reliably enhances concrete frost resistance. However, some researchers believe that the role of air entrainment diminishes sharply at low W/C ratios. To improve concrete strength, the introduction of damping additives capable of relaxing induced stresses is recommended. Studies have shown that gel-like products of cement hydration can serve as damping additives, and their stability can be enhanced by binding portlandite in cement paste with active mineral additives, among which micro-silica is one of the most active representatives **(Matyukhina, A. A., et al. 2017).**

Reducing the W/C ratio and increasing the micro-silica content decreases air volume and increases compressive strength. Furthermore, concrete frost resistance improves, reaching a maximum when the micro-silica content is 20%. For concrete specimens of this composition, minimal strength variation was observed during testing, indicating the highest stability of the cement paste structure.

Thus, at low air content, the matrix's relaxation properties, determined by the permeability of cement paste, pore size, and the number of crystalline and gel-like cement hydration products, play a critical role in ensuring concrete strength under frost impact without air-entraining additives. The

introduction of micro-silica leads to an increase in low-base calcium hydrosilicates of the C-S-H type. Compared to high-base hydrosilicates, these hydrates exhibit greater stability and strength due to an increase in strong Si-O-Si siloxane bonds and a decrease in weak Ca-O ionic bonds. A reduction in portlandite crystals decreases the crystalline hydrate component and the number of stress concentrators, thereby enhancing crack resistance in cement paste. In the contact zone between cement paste and aggregates, the reduction of $Ca(OH)_2$ crystals contributes to increased strength, and the porosity and size of crystalline phases in cement paste also decrease **(Duballet, R., Baverel, O., & Dirrenberger, J. 2017).**

High frost resistance is also ensured by the stability of hydrated phases resulting from the effect of micro-silica additives. Therefore, the key factors in ensuring the durability of road concrete are:

- Low initial W/C ratios that ensure reduced capillary porosity and water saturation;
- Structural characteristics of cement paste, including increased cement gel content and a free $Ca(OH)_2$ content not exceeding 1.0%, which slows down gel phase aging and facilitates stress relaxation;
- Recommendations for road concrete with frost resistance grades of F500–F600 without air-entraining additives include W/C ratios of 0.25–0.30 and mandatory introduction of hydrogen-releasing components along with micro-silica additives up to 15–20% of the cement mass;
- Capillary porosity of concrete and the amount of free calcium hydroxide in cement paste can serve as predictive criteria for the durability of road concrete used under cyclic freezing conditions in de-icing solutions.

4 RESULTS AND DISCUSSION

As **Figure 2** illustrates, nano-silica was added to fine-grained concrete in proportions of 0.05%, 0.10%, 0.25%, and 0.5% of the cement mass, and the workability of the prepared mixture was determined by measuring the slump of the cone.

Figure 2 - Effect of Nano-Silica Content on the Workability of the Mixture

The analysis of the results revealed that in mixtures with nano-silica, the cement-to-water ratio remained consistent, but the workability of the mixture decreased. This indicates that within the studied range, the addition of nano-silica reduces the mobility of the mixture.

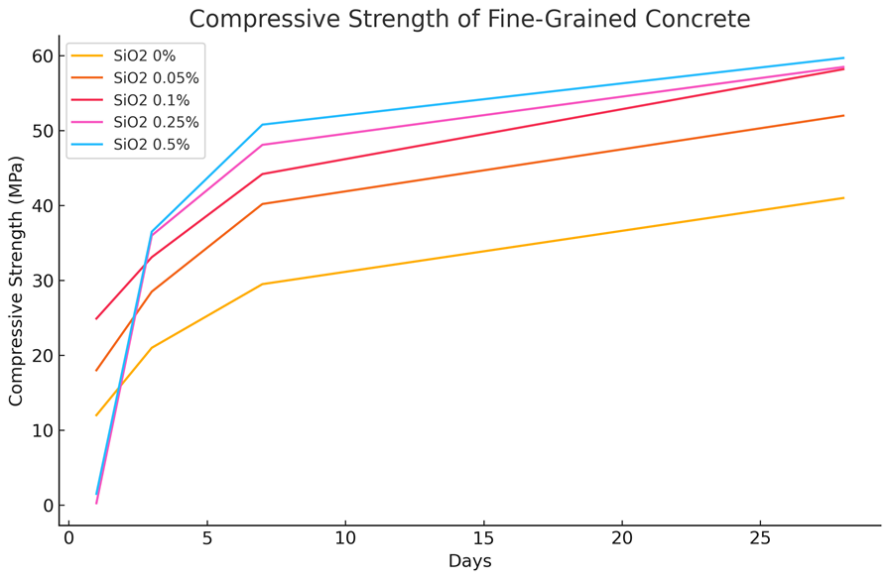

Figure 3 - Variation in Compressive Strength (MPa) of Fine-Grained Concrete with the Addition of Nano-Silica

As **Figure 3** demonstrates, the results of the experimental studies reveal the effect of nano-silica content on the compressive strength of fine-grained concrete. Meanwhile, **Figure 4** illustrates the strength gain over 3, 7, and 28 days at various nano-silica contents with a water-to-cement ratio of 0.45.

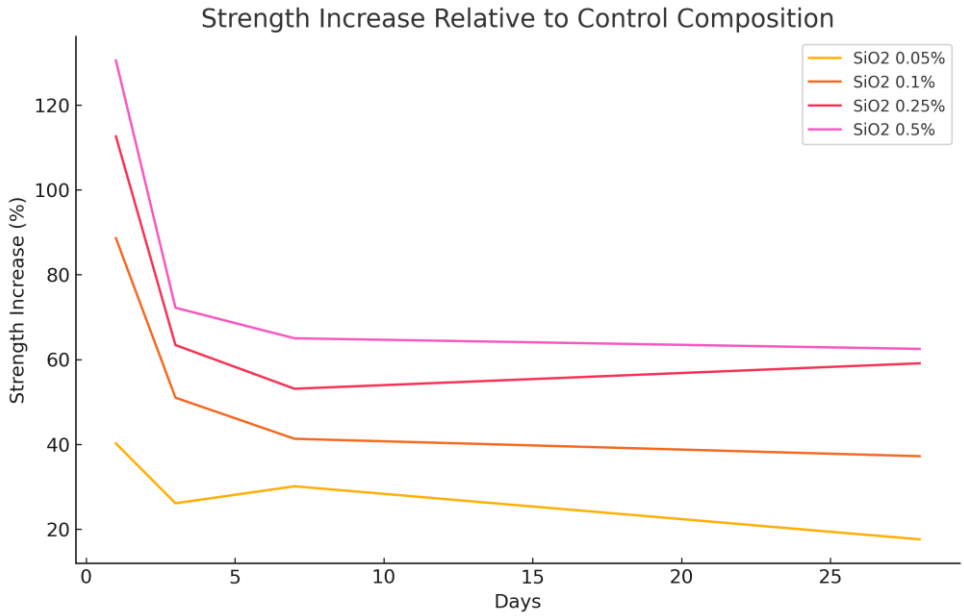

Figure 4 - Strength improvement of fine-grained concrete in comparison with the control mix.

As **Figure 5** illustrates, the rate of strength development of fine-grained concrete with the addition of nano-silicon dioxide is presented.

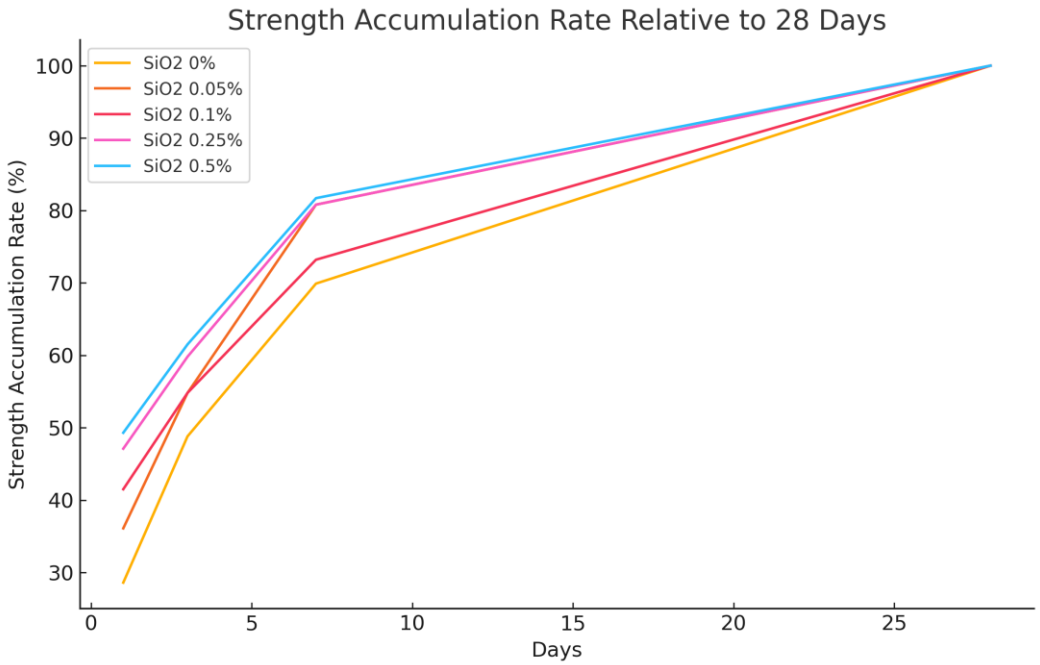

Figure 5 - The rate of strength development of fine-grained concrete (relative to 28 days).

The analysis of experimental data determined the effect of the nano-additive on the strength and rate of strength growth. When the nano-additive was introduced, the strength increased by 1.4 times on the first day, by 74.6% on the third day, by 65.7% on the seventh day, and by 42.0% on the 28th day. The maximum hardening was achieved with the addition of 0.5% nano-silica. The rate of increase in compressive strength rises with the addition of nano-silica, especially affecting the concrete during the first and third days of hardening. This suggests that the use of nano-additives can produce fast-hardening concrete.

As several scientists **(Nematollahi et al., 2017; Verian et al., 2020)** have noted, the obtained results regarding the increase in the solution's strength can be attributed to the nanostructure formed by the addition of nano-silica particles. These particles, characterized by a large specific surface area and high physicochemical activity, accelerate the hydration rate of cement. Consequently, the directed formation of calcium silicate hydrates occurs, which structures the cement matrix and enhances its strengthIn addition, the positive effect of nano-silica in cement compositions is explained by the pozzolanic reaction, as a result of which nano-silica binds free calcium hydroxide to form high-strength, low-basic calcium hydroxysilicates.

$$SiO_2 + Ca(OH)_2 + H_2O = mCaO{\cdot}nSiO_2{\cdot}qH_2O$$

The use of nano-silica additives leads to increased strength, along with additional possible effects, such as improved sulfate resistance, frost resistance, and chloride migration resistance, etc. Thus, the analysis of the effect of nano-silica revealed that when nano-silica was added, the compressive strength increased by 1.4 times on the first day, by 74.8% on the third day, by 64.8% on the seventh day, and by 42.8% on the 28th day. The addition of nano-silica allows for the production of fast-hardening concrete with high strength.

5 CONCLUSIONS

This study demonstrates that the incorporation of nano-silica ash in fine-grained concrete significantly enhances its efficiency compared to micro-silica. By requiring 50 times less material to achieve comparable improvements in compressive and flexural strength, nano-silica presents a highly effective alternative. Additionally, its compatibility with standard technological regulations makes it a practical choice for the production of ready-mix and precast concrete. Beyond strength enhancement, nano-silica also contributes to increased sulfate resistance, improved frost durability, and greater resistance to chloride ion migration. However, to maximize its effectiveness, it is crucial to prevent particle agglomeration during production. This can be achieved by optimizing vacuum sublimation processes or refining incorporation techniques in concrete mixtures. Future research should focus on further improving the dispersion methods of nano-silica and evaluating its long-term performance in various environmental conditions.

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RESEARCH ARTICLE

IMPROVING EFFICIENCY IN 3D PRINTING THROUGH MODIFICATION OF FINE-GRAINED CONCRETE COMPOSITION

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Abstract. *Additive manufacturing, also known as three-dimensional printing (3D printing), has many advantages over traditional construction technologies, including high construction efficiency, less construction waste, and significantly reduced labor costs. Nowadays, additive technologies are becoming increasingly popular in various fields, including the construction industry. One of the most effective ways to regulate and ensure the required technological and construction properties of concrete mixtures in concrete technology, including 3D printing, is by using various modifying additives. The introduction of active mineral additives into concrete mixes allows for reduced cement consumption, increased cement stone density, improved water resistance, and decreased permeability. This article presents the results of a study on the effect of mineral additives on the properties of cement paste, shape stability, and physicomechanical characteristics of fine-grained concrete in additive manufacturing technology, aiming to select the most effective mineral components for the production of cement materials for 3D printing. The optimization of the structure to form a dense and hermetic high-quality concrete structure based on cement binders can be achieved by introducing finely dispersed mineral additives of various compositions. The study examines the effect of mineral additives on the normal density and setting time of Portland cement, the kinetics of plastic strength gain in cement systems over time depending on the type and concentration of additives and the type of Portland cement, the ultimate shear stress of the concrete mixture, the formability of the mixture, the dimensional stability of the layers, and the physicomechanical characteristics of the hardened composites.*

Keywords: *3D printing, Portland cement, fine-grained concrete, mineral additives, modifying additives.*

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ҰСАҚ ТҮЙІРШІКТІ БЕТОННЫҢ ҚҰРАМЫН ӨЗГЕРТУ АРҚЫЛЫ 3D БАСЫП ШЫҒАРУДАҒЫ ТИІМДІЛІКТІ АРТТЫРУ

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Аңдатпа. *Үш өлшемді басып шығару (3D басып шығару) аддитивті өндіріс дәстүрлі құрылыс технологияларына қарағанда көптеген артықшылықтарға ие, яғни құрылыс тиімділігі жоғары, құрылыс қалдықтары аз және еңбек шығындары айтарлықтай төмен болады. Қазіргі уақытта аддитивті технологиялар әр түрлі салаларда, соның ішінде құрылыс индустриясында танымал бола бастады. Бетон технологиясында, соның ішінде 3D басып шығаруда бетон қоспаларының қажетті технологиялық және құрылыс-техникалық қасиеттерін реттеу мен қамтамасыз етудің тиімді әдістерінің бірі әртүрлі модификациялық қоспаларды қолдану болып табылады. Бетон қоспаларына белсенді минералды қоспаларды енгізу цемент шығынын үнемдеуге, цемент тасының тығыздығын, суға төзімділігін арттыруға және өткізгіштігін төмендетуге мүмкіндік береді. Бұл мақалада 3D басып шығару технологиясында цемент материалдарын өндіруге арналған ең тиімді минералды компоненттерді таңдау мақсатында минералды қоспалардың цемент қоспасының қасиеттеріне, пішінге төзімділігіне және аддитивті өндіріс технологиясындағы ұсақ түйіршікті бетонның физикалық-механикалық сипаттамаларына әсерін зерттеу нәтижелері келтірілген. Цемент байланыстырғыштарында жоғары сапалы бетонның тығыз және герметикалық құрылымын қалыптастыру үшін құрылымды оңтайландыру әр түрлі құрамдағы ұсақ дисперсті минералды қоспаларды енгізу арқылы жүзеге асырылуы мүмкін. Сондай-ақ, минералды қоспалардың портландцементтің қалыпты тығыздығы мен қатаю уақытына әсері, қоспалардың түрі мен концентрациясына және портландцемент түріне байланысты уақыт бойынша цемент жүйелерінің пластикалық беріктігі жиынтығының кинетикасы, бетон қоспасының шекті ығысу кернеуі, қоспаның қалыптылығы, қабаттардың пішінге төзімділігі, қатайтылған композиттердің физика-механикалық сипаттамалары зерттелді.*

Түйін сөздер: *3D басып шығару, портландцемент, ұсақ түйіршікті бетон, минералды қоспалар, модификациялық қоспалар.*

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НАУЧНАЯ СТАТЬЯ

ПОВЫШЕНИЕ ЭФФЕКТИВНОСТИ В 3D ПЕЧАТИ ПУТЕМ МОДИФИКАЦИИ СОСТАВА МЕЛКОЗЕРНИСТОГО БЕТОНА

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Аннотация. *Аддитивное производство, также известное как трехмерная печать (3D печать), имеет множество преимуществ перед традиционными строительными технологиями, включая высокую эффективность строительства, меньшее количество строительных отходов и значительное сокращение трудозатрат. В настоящее время аддитивные технологии становятся все более популярными в различных областях, в том числе и в строительной отрасли. Одним из эффективных способов регулирования и обеспечения, требуемых технологических и строительно-технических свойств бетонных смесей в технологии бетонов, в том числе при 3D-печати, является применение различных модифицирующих добавок. Введение активных минеральных добавок в состав бетонных смесей позволяет экономить расход цемента, повышать плотность цементного камня, водостойкость, снижать проницаемость. В этой статье представлены результаты исследования влияния минеральных добавок на свойства цементного теста, формоустойчивость и физико-механические характеристики мелкозернистого бетона в технологии аддитивного производства, с целью выбора наиболее эффективного минеральные компоненты для изготовления цементных материалов для 3D-печати. Оптимизация структуры с целью формирования плотной и герметичной структуры высококачественного бетона на цементных вяжущих может быть осуществлена путем введения мелкодисперсных минеральные добавки различного состава. А также исследовано влияние минеральных добавок на нормальную густоту и сроки схватывания портландцемента, кинетику набора пластической прочности цементных систем во времени в зависимости от вида и концентрации добавок и вида портландцемента, предельное напряжение сдвига бетонной смеси, формуемость смеси, формоустойчивость слоев, физико-механические характеристики затвердевших композитов.*

Ключевые слова: *3D печати, портландцемент, мелкозернистый бетон, минеральные добавки, модификационные добавки.*

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CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

АЛҒЫС / ҚАРЖЫЛАНДЫРУ КӨЗІ

Зерттеу Қазақстан Республикасы Ғылым және жоғары білім министрлігі Ғылым комитетінің гранттық қаржыландыру шеңберінде жүргізілді (грант № «BR21882278 Аккредиттелген мамандардың толық циклін қамтамасыз ету үшін құрылыс-техникалық инженерлік орталық құру» Қазақстан Республикасының құрылыс, жол құрылысы саласындағы қызметтері»).

МҮДДЕЛЕР ҚАҚТЫҒЫСЫ

Авторлар мүдделер қақтығысы жоқ деп мәлімдейді.

БЛАГОДАРНОСТИ/ИСТОЧНИК ФИНАНСИРОВАНИЯ

Исследование проводилось в рамках грантового финансирования Комитета науки Министерства науки и высшего образования Республики Казахстан (грант № BR21882278 «Создание строительного инженерно-технического центра для обеспечения полного цикла аккредитованных специалистов» в сфере строительства и дорожного строительства Республики Казахстан).

КОНФЛИКТ ИНТЕРЕСОВ

Авторы заявляют, что конфликта интересов нет.

1 INTRODUCTION

3D printing technology is currently one of the most advanced technologies that help increase the efficiency of construction and save all types of resources.

3D printing is an additive construction technology that allows for the creation of a complete building structure of any complexity using a digital model and a 3D printer that uses various materials in a short time (**Lesovik, 2021**).

The main problem with the widespread adoption of such technologies is the lack of integrated solutions for designing printable walls that meet structural and thermal requirements, as well as the lack of available materials that enable the production of mixtures for building printing that are optimized for the features of a 3D printer. At the same time, an important condition for the economic attractiveness of 3D technologies is the minimization of initial costs, as well as the availability of the raw material base, which is currently a key driver of innovation.

To date, mixtures based on Portland cement have received significant scientific study and practical application in the field of building printing. There are well-known studies aimed at finding ways to increase their effectiveness through the use of chemical and mineral additive complexes (**Lin et al., 2017**), modification of the cement binder base (**Slavcheva et al., 2021**), and the use of special technological techniques for their production (**Reiter et al., 2018**). At the same time, cement types themselves are characterized by high energy consumption during production, and concrete based on them often has suboptimal rheological properties for building printing and a tendency toward increased early strength.

Despite the attractiveness of the new technological solution for the construction of building structures and judging by existing international experience in implementing this process, there are many problems that must be addressed before the potential of 3D printing in construction can be fully realized. Fine-grained concrete based on cement binders, being the most common and affordable construction material, forms the basis for the adoption of 3D printing technology in construction (**Duballet et al., 2019**), both in Kazakhstan and in other countries.

A wealth of theoretical and practical experience, as well as expert knowledge, has been accumulated worldwide in the field of fine-grained concrete. This knowledge can be used to formulate requirements for cement-based 3D printing materials and to optimize and standardize their formulations to improve quality. One of the key characteristics of high-quality and high-strength concretes, unlike traditional ones, is the presence of a highly dispersed mineral additive in the composition. This additive modifies the structure of the mixture, regulating its mobility and affecting the density and strength of the composite (**Verian et al., 2020**).

This can be achieved using mineral additives of natural or artificial origin. The use of these additives, also known as supplementary binders, not only reduces environmental damage but also lowers the cost of concrete and improves some of its properties (**Chernysheva, 2019**).

This article presents the results of experimental studies on modifying the basic composition of fine-grained concrete used in 3D printing to enhance the efficiency of additive manufacturing in construction by improving its formability, shape stability, and physical-mechanical properties.

2 LITERATURE REVIEW

One of the most effective ways to regulate and ensure the required technological and construction properties of concrete mixtures in concrete technology, including 3D printing, is the use of various modifying additives. The introduction of active mineral additives into concrete mixes allows for reduced cement consumption, increased density of cement stone, improved water resistance, and decreased permeability.

An analysis of classifications of mineral additives in cements, concretes, and mortars according to regulatory sources indicates the absence of their differentiation based on their influence on the

rheological properties of mixtures. This is an important factor for the effective use of mineral additives in 3D printing technology.

A review of the literature allows us to consider composition and rheological properties of molding mixtures based on composite gypsum binder (**Chernysheva, 2021**) which, to a certain extent, takes into account their influence on rheological properties.

Considering the experience of using groups of additives, it should be noted that finely ground lime flour (with a particle size of 2.9 microns) is used as a rheologically active additive when ground together with cement and a 1% plasticizing additive. The authors obtained a concrete mix with a mobility of 12.5 cm, which does not meet the requirements for the use of such mixtures in 3D printing. Additionally, the strength characteristics of concrete slightly decreased in the samples obtained by the authors.

Regarding reactive additives, it is important to highlight the effectiveness of silica in increasing the strength of fine-grained concrete-based products (**Chen, 2020**). Its introduction in an amount of 12% increases compressive strength by 55% and bending strength by 14%, due to the binding of free calcium hydroxide into low-base calcium hydrosilicates, which have high durability. It is also known that clay calcined at a specific temperature and ground to 250-800 m²/kg can be used as a reactive additive (**Shinkevich, 2019**), allowing for an increase in the average density and softening coefficient of cement stone.

Several studies indicate the effectiveness of using various mineral additives in cement systems for 3D printing technology, including metakaolin (**Chen, 2020**), clay in the form of bentonite (**Mendoza Reales, 2019**), diatomite, microcrystalline silicon (**Han, 2021**), and others. Additionally, kaolin and wollastonite are used to regulate the plastic properties of molded masses (**Zareei, 2019**).

However, when developing concrete mixes for 3D printing, particular attention should be paid to rheological properties, which directly affect geometric changes caused by the spreading of underlying layers. This factor largely determines the quality of the molded product.

Currently, no standardized criterion exists for assessing the effectiveness of 3D printing that accounts for geometric changes in construction products due to the spreading of underlying layers, depending on the presence of modifying additives, particularly mineral additives.

Numerous studies have examined the effects of mineral additives on the structure and properties of composites based on cements of various mineralogical compositions in combination with different chemical additives (**Ibragimov, 2023**). Several authors have proposed classifications of mineral additives based on various criteria, which is highly useful for their application and effectiveness analysis. However, the impact of different types of mineral additives on the formation of structure and properties of 3D-printed concrete, as well as on achieving optimal rheological properties of concrete mixtures and physicomechanical properties of the hardened composite, remains insufficiently studied. This underscores the necessity for further experimental research in this field.

3. MATERIALS AND METHODS

The effects of mineral additives with different mineralogical compositions and hydraulic activities on the normal density, setting time, kinetics of cement dough strength gain, ultimate shear stress of fine-grained concrete mixtures at the boundary of gravitational spreading, and the physicomechanical characteristics of fine-grained concrete printed using a 3D printer were investigated.

Table 1 presents the results of determining the hydraulic activity of mineral additives.

Table 1

Activity of the studied mineral additives [author's materials]

№	Name of mineral additives	Activity, mg/g	Content SiO_2,%	Content Al_2O_3, %
1	**2**	**3**	**4**	**5**
1	Diatomite	1653,8	93,00	4,60
2	Microsilica	1617,3	92,40	0,60
3	Biosilicon	1500,6	88,20	5,10
4	Metakaolin	1343,8	49,36	32,25

According to **Table 1**, diatomite, microsilicon, biosilicon, and metakaolin exhibit the highest hydraulic activity (in descending order).

The results of studies on changes in the normal density and setting time of Portland cement CEM I 42.5N, depending on the amount of additives with various mineral compositions, are presented in **Table 2**.

Table 2

The effect of mineral additives on the normal density and setting time of Portland cement CEM I 42.5N

Name of mineral additives	The content of mineral additives, %	Setting time		Normal density, %
		beginning	end	
1	2	3	4	5
-	-	3 h 30 min	4 h 48 min	32,39
Diatomite	20	3 h 36 min	5 h 09 min	42,08
	30	3 h 43 min	4 h 55 min	48,05
	40	4 h 08 min	5 h 14 min	55,11
	50	4 h 23 min	5 h 58 min	58,33
Microsilica	20	3 h 45 min	4 h 43 min	33,36
	30	4 h 34 min	5 h 45 min	36,73
	40	5 h 00 min	5 h 53 min	39,56
	50	5 h 03 min	5 h 55 min	39,77
Biosilicon	20	2 h 39 min	4 h 12 min	38,19
	30	4 h 07 min	4 h 57 min	42,08
	40	4 h 00 min	5 h 15 min	47,35
	50	3 h 41 min	5 h 11 min	52,66
Metakaolin	20	3 h 06 min	4 h 30 min	37,46
	30	3 h 38 min	5 h 02 min	43,08
	40	3 h 57 min	5 h 22 min	48,24
	50	3 h 43 min	5 h 30 min	51,77
Kaolin	20	4 h 12 min	5 h 15 min	38,93
	30	4 h 22 min	5 h 16 min	42,39
	40	4 h 38 min	6 h 05 min	45,16
	50	4 h 39 min	6 h 06 min	48,65
Wollastonite	20	3 h 34 min	4 h 31 min	35,29
	30	3 h 43 min	4 h 45 min	37,45
	40	4 h 18 min	5 h 21 min	40,53
	50	3 h 50 min	5 h 04 min	42,24

As seen in **Table 2**, all the studied mineral additives lead to an increase in the normal binder density by 3.2–85.4% compared to the additive-free composition. The smallest increase in normal binder density is observed when using a microsilicon additive (3.2–24.9%, depending on its content), while the largest increase is recorded with the addition of diatomite (32.3–85.4% compared to the additive-free composition). The use of silica at a 10% concentration by weight of Portland cement reduces the setting time by 5 minutes compared to the additive-free composition. The introduction of 10% biosilicon reduces the initial and final setting times by 51 minutes and 36 minutes, respectively. Similarly, 10% metakaolin reduces these times by 36 minutes and 18 minutes. Wollastonite, when added at 10–20% by weight of Portland cement, decreases the setting time by 4–17 minutes compared to the additive-free composition.

Conversely, the remaining additives in the studied concentrations lead to an increase in the setting time compared to the additive-free composition: initial setting time increases by 6–67 minutes, final setting time increases by 71–79 minutes.

To assess the effect of mineral additives on the rheological properties of fine-grained concrete mixtures, experimental studies were conducted on the maximum shear stress of concrete mixtures containing the studied mineral additives, based on Portland cement CEM I 42.5N and sand with a grain Finenes modulus FM 2.3 and FM 2.4.

According to the results of trial 3D printing of fine-grained concrete with different mobility levels, it was found that concrete mixtures with mineral additives but without Portland cement of mobility grade Dc 2 exhibited defect formation, such as tears, due to changes in rheological properties affecting extrusion. In this regard, a concrete mix with mobility grade Dc 3 (corresponding to a cone immersion depth of 8.9 cm) was selected for further research. Mineral additives were introduced as a partial replacement for quartz sand. The research results are presented in **Tables 3** and **4.**

Table 3
Effect of Mineral Additives on the Ultimate Shear Stress of Concrete Mixtures with Portland Cement CEM I 42.5N and Sand with a Grain Size Modulus of FM 2.4

Type of mineral additives	The content of mineral additives, %	The density of the concrete mix, kg/m^3	Maximum shear stress, Pa
1	**2**	**3**	**4**
-	-	2227	81
Diatomite	20	2186	57
	30	2115	55
	40	2056	48
	50	1968	51
Microsilica	20	2203	45
	30	2150	43
	40	2074	47
	50	1991	44
Biosilicon	20	2174	71
	30	2133	56
	40	2080	69
	50	2050	61
Wollastonite	20	2197	63
	30	2180	56
	40	2177	70
	50	2174	68

Table 4
The effect of mineral additives on the ultimate shear stress of concrete mixtures in Portland cement CEM I 42.5N and sand with a grain size modulus FM 2.3

Type of mineral additives	The content of mineral additives, %	The density of the concrete mix, kg/m^3	Maximum shear stress, Pa
1	**2**	**3**	**4**
-	-	2191	99
Kaolin	20	2174	78
	30	2127	75
	40	2086	74
	50	2066	73
Metakaolin	20	2133	94
	30	2139	69
	40	2121	67
	50	2101	64

As shown in **Table 3,4** all the studied mineral additives reduce the limiting shear stress by 6.7–49.3% to varying degrees compared with the additive-free composition. This reduction is caused by an increase in the water demand of the modified formulations (**Table 2**) to achieve the required mobility. As a result, the density of the mixture decreases, and its ability to spread increases. However, the obtained data do not fully allow for assessing changes in the viscoplastic properties of fine-grained concrete mixtures due to the limitations of this methodology (which considers only the boundary of gravitational spreading). This approach does not account for the shear stress values of the system while considering the viscosity of the mixture at different shear rates.

Therefore, further studies on the shape stability of the mixture were conducted during layer-by-layer extrusion, as the values of limiting shear stress and shear rate are closer to the actual conditions in 3D printing technology.

At the next stage, the influence of the type and content of mineral additives (MD) on the shape stability of the mixture was studied. The assessment was based on the maximum number of layers of the concrete mixture printed without technological interruption under the following conditions: Portland cement CEM I 42.5N; Sand with a grain size modulus FM 2.3 and FM 2.4; Mobility grade Dc 3 (corresponding to a cone immersion depth of 8.9 cm). The research results are shown in **Figures 1–6**.

During the 3D printing process, it was observed that fine-grained concrete mixes with mineral additives exhibited better formability during layer-by-layer extrusion compared to both: the base unmodified composition; compositions containing plasticizing additives. This improvement was reflected in the uniformity of the extruded mixture and a reduced number of defects during molding.

As seen in **Figures 1–6**, the introduction of the studied mineral additives significantly affects the shape stability of the fine-grained concrete mixture. Despite the decrease in the maximum shear stress at the boundary of gravitational spreading, the maximum number of printed layers without technological interruption increases.

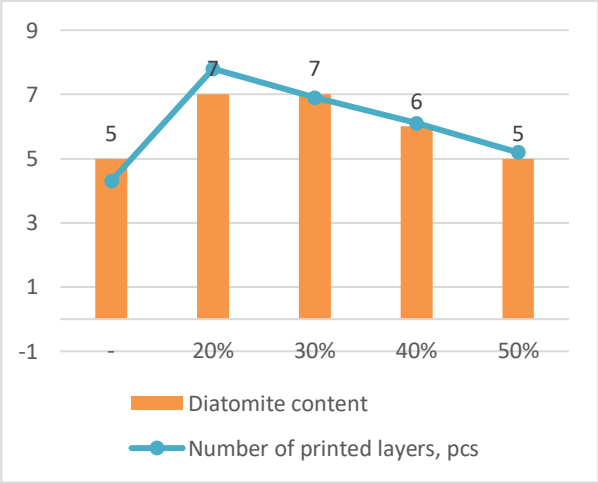

Figure 1 – The effect of the diatomite content on the shape stability of a fine-grained concrete mixture based on cement CEM I 42.5N and sand with FM 2.4

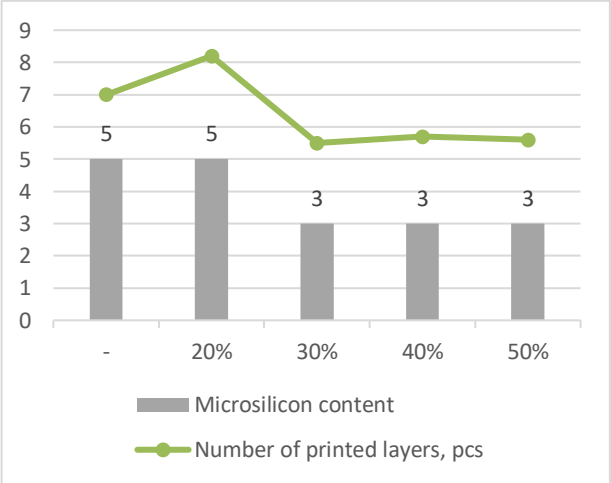

Figure 2 – The effect of the silica content on the shape stability of a fine-grained concrete mixture based on cement CEM I 42.5N and sand with FM 2.4

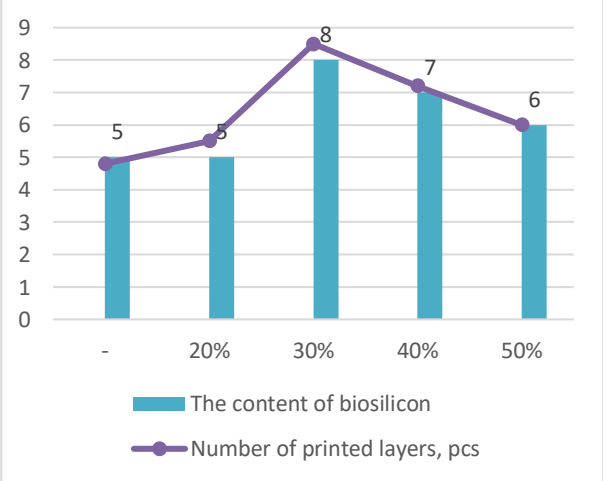

Figure 3 – The effect of the biosilicon content on the shape stability of a fine-grained concrete mixture based on Portland cement CEM I 42.5N and sand with FM 2.4

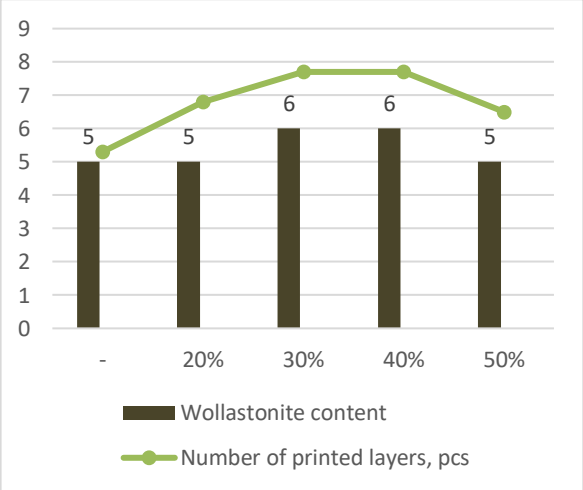

Figure 4– The effect of the wollastonite content on the shape stability of a fine-grained concrete mixture based on cement CEM I 42.5N and sand with FM 2.4

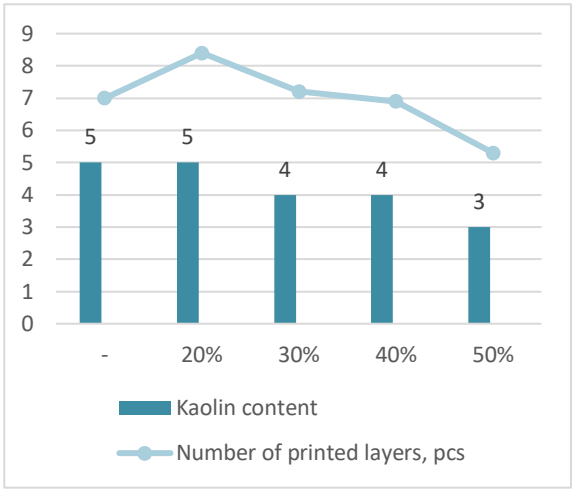

Figure 5 – Effect of kaolin content on the shape stability of fine-grained concrete mix on Portland cement CEM I 42.5N and sands with FM 2.3

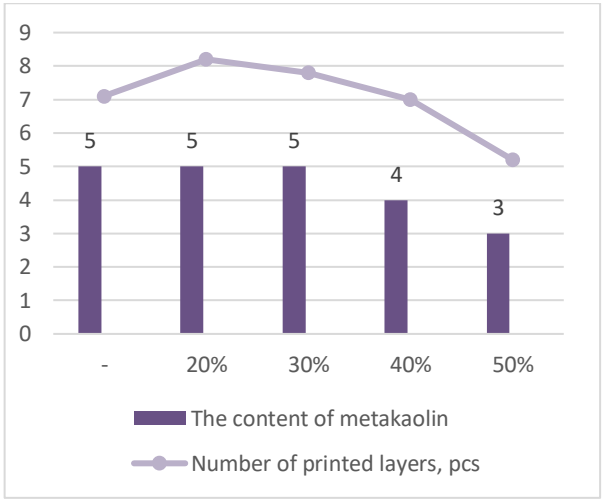

Figure 6 – The effect of the metacaolin content on the shape stability of a fine-grained concrete mixture based on cement CEM I 42.5N and sand with FM 2.3

Figure 7 – Photofixation of the fracture process (loss of shape stability with displacement of the printed layers) of a sample printed on a 3D printer

Finally, the studied mineral additives led to an increase in water absorption (except for the following cases): Microsilicon; Biosilicon (at 10% by weight of Portland cement); Metakaolin (at 30–40% by weight of Portland cement). For all other additives, water absorption increased by 6.0–96.4% compared with the control composition.

4. RESULTS AND DISCUSSION

The most notable improvement in shape stability—by 40% and 60% (i.e., 2 and 3 additional layers)—was observed for mixtures containing: 20% biosilicon: 10–20% diatomite. For all studied mineral additives, the highest number of printed layers without interruption was observed at an optimal additive content of 10–20%. This phenomenon is attributed to the interparticle forces within the mixture. With the introduction of mineral additives (particle sizes 0.5–3 μm) at 10–20% by weight of Portland cement, the dominance of flocculation and colloidal interactions increases. This leads to: greater cohesion of the mixture; Better formability; Higher shape stability.

However, when the mineral additive content exceeds 20%, the water demand increases due to the high specific surface area of the solid particles required to maintain the given mobility. This results in: decreased mixture density (**Table 3,4**); increased thickness of the solvate shell of colloidal particles; reduced flocculation (i.e., less attraction between positively and negatively charged particles, forming fewer floccules); increased free water in the system. Consequently, the excessive

increase in sliding between solid particles due to repulsive forces reduces the dimensional stability of the mixture.

It is important to note that failure in freshly formed samples with mineral additives was characterized by incomplete overturning—similar to compositions containing plasticizing additives. Upon reaching a critical force, loss of mold stability was observed, leading to displacement of printed layers (**Figure 7**).

When determining the shape stability of the mixture, the maximum number of printed layers was compared to the total height of these layers without technological interruption. It was found that different total heights could correspond to the same number of printed layers (**Figures 1–6**). Therefore, this phenomenon should be considered when assessing the shape stability of a concrete mix.

5 CONCLUSIONS

The conducted studies have shown that the examined mineral additives generally have a positive effect on the formability of the extruded mixture. They improve cohesion and uniformity while reducing the occurrence of tears and other defects during 3D printing. Special attention should be paid to the ability of mineral additives to enhance the shape stability of printed layers, which is crucial for 3D printing technology. In this regard, the most effective types and contents of mineral additives were determined not only from the standpoint of ensuring high physico-mechanical properties of concrete but also in terms of enhancing the form stability of the mixture with a given mobility, considering the technological parameters and features of the 3D printer. Among the studied mineral additives, biosilicon and diatomite were found to be the most effective in improving the form stability of the mixture. At the same time, any reduction in the physico-mechanical properties of fine-grained concretes containing mineral additives in 3D-printed structures can be compensated by using Portland cement and complex additive formulations.

The analysis of the influence patterns of the studied mineral additives on the properties of cement dough and fine-grained concrete in additive manufacturing technology allowed us to determine the following:

1. All studied mineral additives lead to an increase in the normal density of cement dough by 3.2–85.4% compared to the additive-free composition, with the largest increase observed for diatomite. The setting time of cement dough containing mineral additives in amounts of 10–40% by weight of Portland cement generally increases (by 6–67 minutes for the initial setting and 71–79 minutes for the final setting).
2. Ensuring equal mobility (Dc 3) results in a reduction of the limiting shear stress by 6.7–49.3% compared to the additive-free composition. However, within the 10–20% range of mineral additive content, an increase in mixture cohesiveness, improved formability, and enhanced shape stability (up to 82.3%) during 3D printing is observed. This is likely due to the intensification of flocculation and the colloidal nature of interactions between solid particles in the system.
3. Mixtures modified with biosilicon (20%) and diatomite (10–20%) are the most effective in enhancing shape stability, achieving increases of 40% and 60%, respectively.
4. For further research, metakaolin, kaolin, and biosilicon will be studied at a concentration of 10% by weight of Portland cement.

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RESEARCH ARTICLE

MONITORING DEFORMATIONS OF ENGINEERING STRUCTURES IN SEISMIC REGIONS

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Abstract. *The article considers the issues of ensuring the safety of operation of engineering structures in seismically hazardous regions, using the example of the transport interchange of Abay Avenue and Sain Street in Almaty, Republic of Kazakhstan. Almaty is located in a zone of increased seismic activity, and a metro line runs along Abay Avenue, which complicates the engineering and geological situation. In such cases, the creation of an effective system for monitoring the condition of structures is of particular importance. An integrated approach is proposed, including an engineering and geological study of the rock massif, satellite GPS technologies, an electronic tacheometer, laser scanning of the earth and an assessment of the accuracy of geodetic measurements. A methodology for constructing a reference geodetic network for monitoring bridges and buildings has been developed. The expediency of using satellite positioning, tacheometry and scanning when monitoring deformations and settlements of structures is substantiated. To install high-precision electronic and laser devices for geomonitoring the earth's surface, the authors have developed a permanent point that ensures speed and accuracy of centering, eliminating the use of tripods. Based on the conducted research, the authors propose methods for determining the settlements and displacements of structures. The results of the research were implemented in the implementation of a scientific project, and also used in the educational process. The practical value of the work lies in the possibility of using the obtained results to improve the level of safety at similar facilities and reduce the risks associated with natural and man-made factors.*

Keywords: *bridge, deformations, monitoring, geodetic reference networks, satellite positioning, geodetic observations, technical condition assessment.*

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СЕЙСМИКАЛЫҚ АЙМАҚТАРДАҒЫ ИНЖЕНЕРЛІК ҚҰРЫЛЫСТАРДЫҢ ДЕФОРМАЦИЯЛАРЫН БАҚЫЛАУ

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Аңдатпа. *Мақалада сейсмикалық қауіпті өңірлерде инженерлік құрылыстарды пайдалану қауіпсіздігін қамтамасыз ету мәселелері, Қазақстан Республикасы, Алматы қаласындағы Абай даңғылы мен Саин көшесінің көлік айрығы мысалында қарастырылған. Алматы қаласы сейсмикалық белсенділігі жоғары аймақта орналасқан, ал Абай даңғылының бойында Метрополитен сызығы өтеді, бұл инженерлік-геологиялық жағдайды қиындатады. Мұндай жағдайларда құрылыстардың жай-күйін бақылаудың тиімді жүйесін құру ерекше маңызға ие. Тау жыныстарының массивін инженерлік-геологиялық зерттеу, спутниктік GPS технологиялары, электронды тахеометр, жерді лазерлік сканерлеу және геодезиялық өлшеулердің дәлдігін бағалауды қамтитын кешенді тәсіл ұсынылды. Көпірлер мен ғимараттарды бақылау үшін тірек геодезиялық желіні құру әдістемесі жасалды. Құрылыстардың деформациялары мен жауын-шашындарын бақылау кезінде спутниктік позициялауды, тахеометрияны және Сканерлеуді қолданудың орындылығы негізделген. Жер бетін геомониторинг кезінде жоғары дәлдіктегі электронды және лазерлік Аспаптарды орнату үшін авторлар штативтерді қолдануды болдырмай, орталықтандырудың жылдамдығы мен дәлдігін қамтамасыз етуге мүмкіндік беретін тұрақты пункт әзірледі. Зерттеу негізінде авторлар құрылымдардың шөгінділері меншмещысуларын анықтау әдістерін ұсынады. Зерттеу нәтижелері ғылыми жобаны орындау кезінде енгізілді, сонымен қатар оқу процесінде қолданылды. Жұмыстың практикалық құндылығы ұқсас объектілердегі қауіпсіздік деңгейін арттыру және табиғи-техногендік факторлармен байланысты тәуекелдерді азайту үшін алынған нәтижелерді қолдану мүмкіндігі болып табылады.*

Түйін сөздер: *көпір, деформациялар, мониторинг, геодезиялық тірек желілер, спутниктік позициялау, геодезиялық бақылаулар, техникалық жағдайды бағалау.*

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НАУЧНАЯ СТАТЬЯ

НАБЛЮДЕНИЕ ЗА ДЕФОРМАЦИЯМИ ИНЖЕНЕРНЫХ СООРУЖЕНИЙ В СЕЙСМИЧЕСКИХ РЕГИОНАХ

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Аннотация. *В статье рассмотрены вопросы обеспечения безопасности эксплуатации инженерных сооружений в сейсмоопасных регионах, на примере транспортной развязки проспекта Абая и улицы Саина в городе Алматы, Республика Казахстан. Город Алматы расположен в зоне повышенной сейсмической активности, а вдоль проспекта Абая проходит линия метрополитена, что усложняет инженерно-геологическую ситуацию. В таких случаях особое значение имеет создание эффективной системы контроля за состоянием сооружений. Предложен комплексный подход, включающий инженерно-геологическое изучение массива горных пород, спутниковые GPS-технологии, электронный тахеометр, лазерное сканирование земли и оценку точности геодезических измерений. Разработана методика построения опорной геодезической сети для наблюдения за мостами и зданиями. Обоснована целесообразность применения спутникового позиционирования, тахеометрии и сканирования при наблюдении деформаций и осадков сооружений. Для установки высокоточных электронных и лазерных приборов при геомониторинге земной поверхности, авторами, разработан постоянный пункт, позволяющий обеспечить быстроту и точность центрирования, исключив применения штативов. На основе проведенного исследования авторами предлагаются методы определения осадок и смещений сооружений. Результаты исследовании внедрены при выполнении научного проекта, а также использованы в учебном процессе. Практическая ценность работы заключается в возможности применения полученных результатов для повышения уровня безопасности на аналогичных объектах и снижения рисков, связанных с природно-техногенными факторами.*

Ключевые слова: *мост, деформации, мониторинг, опорные геодезические сети, спутниковое позиционирование, геодезические наблюдения, оценка технического состояния.*

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CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

АЛҒЫС/ҚАРЖЫЛАНДЫРУ КӨЗІ

Зерттеу Қазақстан Республикасы Ғылым және жоғары білім министрлігі Ғылым комитетінің IRN AP23489269 «Өнеркәсіптік сенімділікті қамтамасыз ету үшін жер қойнауын игеру кезінде тау жыныстары массивінің геологиялық-құрылымдық ортасының геодинамикалық жай-күйінің геотехникалық мониторингі» гранттық қаржыландыру шеңберінде жүргізілді.

МҮДДЕЛЕР ҚАҚТЫҒЫСЫ

Авторлар мүдделер қақтығысы жоқ деп мәлімдейді.

БЛАГОДАРНОСТИ/ИСТОЧНИК ФИНАНСИРОВАНИЯ

Исследование проводилось в рамках грантового финансирования Комитета науки Министерства науки и высшего образования Республики Казахстан IRN AP23489269 «Геотехническое мониторирование геодинамического состояния геолого-структурной среды массива горных пород при освоении недр для обеспечение промышленной надежности».

КОНФЛИКТ ИНТЕРЕСОВ

Авторы заявляют, что конфликта интересов нет.

1 INTRODUCTION

In recent years, many transport interchanges have been built in the city of Almaty, one of them is the intersection of Abay Avenue and Saina Street.Almaty is located in specific engineering and geological conditions and is in the zone of influence of the strongest earthquakes of the Northern Tien Shan. In addition, from east to west along Abay Avenue, a subway is being built. The peculiarity of the construction of the subway in the city of Almaty is that it has a number of complex geotechnical factors, which are:

1. Seismic activity in the city is very high and reaches 9-10 points on the MSK-64 scale.
2. The relief is sloping, as it is located in the area of an intermountain depression.
3. The presence of tectonic faults.
4. The depths of station tunnels and transfer stations vary; there are shallow areas from 11 meters and deep components of 60 meters.

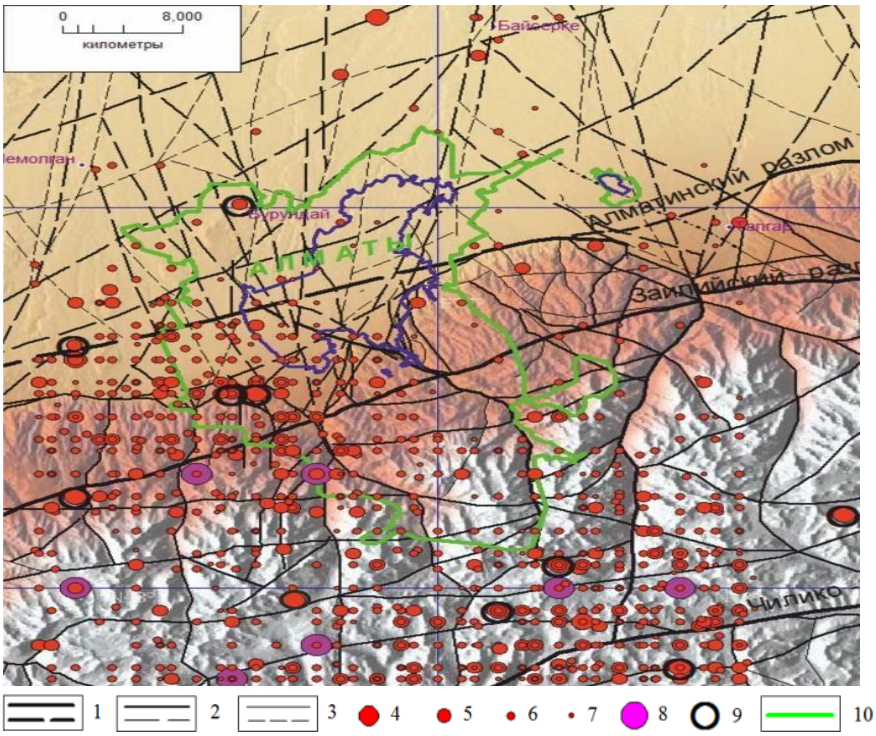
Despite such difficult conditions, andintensive development of the city of Almaty,expressed in changes in its layout, the emergence of new large engineering structures, such as transport interchanges and long bridges within the city limits, the expansion of boundaries affects the size and load of geological faults. In these conditions, the problem of forecasting the technical condition of buildings under construction and in operation becomes acute. Its solution is provided by geodetic monitoring. The object of the study is the transport interchange at the intersection of Abay Avenue and Saina Street (**Figure 1**).

Figure 1 – Transport interchange along Abay Avenue – Saina Street.

*Geological structure.*In geomorphological terms, the site under survey is located within the foothill sloping plain extending north from the foothills of the Zailiyskiy Alatau. Alluvial-proluvial Upper Quaternary deposits participate in the geological and lithological structure of the site. In lithological terms, they are represented by pebble soils overlain by loess-like loams, rarely by sandy loams. For detailing the geological and lithological section, 51 test boreholes, 10.0-18.0 m deep each, were drilled on the site. A total of 806.0 running meters were drilled, including 49.0 m by test boreholes (on bulk soils). Below, pebble soils with sand filler up to 20-30%, low-moisture, with inclusion of boulders up to 25-30%, are exposed (in wells NN1; 4; 5; 7; 8; 11; 12 to a depth of 6.0-6.7 m pebble soils with loamy filler). The exposed thickness of pebble soils is 4.9-14.2 m. **(Nusipov E. et al., 2001), (Medeu A. et al., 2018)**.

*Engineering and seismic conditions of the construction site.*The site of the transport interchange is located in the zone of possible manifestation of the Almaty tectonic fault, which is confirmed by the results of the archive materials of the Kazakh Geotechnical Research Institute (KazGII).

On **Figure 2** the map of earthquake epicenters for 2005-06.2020 and the tectonics of the Almaty region in a 60x70 km contour on a topographic map are presented. In addition to the epicenters of modern earthquakes, the map shows the epicenters of strong earthquakes from historical times with a magnitude of 5.5 or more, as well as active faults (**Nurpeisova M. et al., 2021**).



Tectonic faults in bedrock and overlain by loose sediments (dotted line): 1 – main faults; 2 – main faults; 3 – secondary faults; Epicenters of earthquakes with magnitude Mpv: 4 – from 4 to 4.7; 5 – from 3 to 4; 6 – from 2 to 3; 7 – up to 2; 8 – Epicenters of strong earthquakes since historical times with magnitude 5.5 and more; 9 – Epicenters of perceptible earthquakes after 2005 with records of strong movements; 10 – contour of Almaty city in 2015.

Figure 2 – Modern seismicity (2005-2020) and tectonics of the Almaty region in a 60x70 km contour on the relief map.

In accordance with this position, the goal was set, the idea was substantiated, and the research objectives were formulated.

2 LITERATURE REVIEW

Ensuring the safety of engineering structures located in seismically active zones requires the use of modern geomonitoring technologies capable of tracking spatial displacements and deformations of structures with high accuracy. One of the most common methods is satellite positioning using GNSS systems. **(Zhang et al., 2023)** discusses the possibilities of GNSS monitoring to control deformations of structures, especially in a complex geodynamic environment. The authors emphasize the effectiveness of RTK and static survey modes for measuring displacements within sub-centimeter accuracy, which is especially important when monitoring objects in dense urban areas and increased seismic activity **(Wu et al., 2021)**. An integrated approach combining GNSS and traditional geodetic methods is actively used in modern monitoring systems. Thus, **(Fan et al., 2024)** emphasize the need to use total station observations in combination with leveling to obtain objective data on vertical and horizontal displacements of structures. This is especially important when monitoring transport infrastructure facilities, where there is a high probability of uneven precipitation and deformations. The use of ground-based laser scanning (TLS) is of great importance in modern research, which makes it possible to obtain detailed point clouds and detect deformations with millimeter accuracy. **(Singh et al., 2023)** demonstrate the effectiveness of TLS in monitoring retaining walls and other engineering structures, where geometric accuracy and 3D visualization are key to assessing technical condition. Additional studies by **Bertacchini and Castagnetti (2012)** confirm the high informative value of TLS for spatial analysis of deformation processes, especially during repeated observations of the dynamics of displacement of structural elements. The integration of laser scanning with GPS measurements

provides comprehensive data on the movement of structures. **(Teng et al., 2024)** describe a combined approach in which TLS is complemented by DGPS, which makes it possible to link point clouds to a single coordinate system and perform high-precision deformation analytics based on spatial and temporal models. A separate area in geomonitoring is the application of satellite radar interferometry (InSAR) methods. **(Okiemute et al., 2018)** studied precipitation in the urban area of Almaty using SBAS-InSAR, identifying zones of deformation activity correlating with engineering and geological conditions. Frontiers in Built Environment also demonstrates the high accuracy of the method for tracking spatiotemporal changes in urbanized areas and in the analysis of anthropogenic factors. Domestic research, in particular the work of **Urazbaev et al. (2021)**, demonstrates the successful implementation of geodetic methods for monitoring the technical condition of structures in Kazakhstan. The authors focus on the creation of geodetic reference networks and the use of high-precision electronic total stations and GNSS receivers for monitoring bridges, buildings and transport interchanges in conditions of difficult soils and seismic mobility of the territory.

Thus, the analysis of existing sources confirms the relevance and scientific validity of an integrated approach to geomonitoring, including satellite positioning, electronic total station, ground-based laser scanning and the creation of stationary geodetic points. The combined use of these technologies makes it possible not only to reliably assess current deformation processes, but also to form an effective emergency prevention system for engineering structures in earthquake-prone regions.

3 MATERIALS AND METHODS

The study was conducted using the example of the transport interchange of Abai Avenue and Sain Street in Almaty, located in a zone of increased seismic activity. Considering the difficult engineering and geological situation caused by the presence of a metro line along the avenue, an integrated approach was implemented, including several stages of geomonitoring using modern geodetic technologies. At the first stage, engineering and geological surveys were carried out to assess the structural and tectonic structure of the rock mass. The physico-mechanical properties of soils were studied, groundwater levels were determined, and possible faults and areas of increased mobility were recorded. The field survey data formed the basis for constructing a model of the engineering and geological situation of the site under study. The next stage was the creation and consolidation of the geodetic reference network. To improve the accuracy of observations, the authors have developed stationary observation points that allow the installation of high-precision electronic and laser devices without using tripods, which eliminates errors associated with centering errors. The coordinates of the points were determined using satellite geodesy (GNSS) in static mode followed by post-processing of the data. Geodetic monitoring was carried out using the following instrumental methods:

• Satellite positioning (GNSS): dual-frequency receivers were used in static and kinematic imaging (RTK) mode, which ensured high accuracy in determining the spatial coordinates of control points on observation objects.

• Electronic total station: used for detailed measurement of horizontal and vertical displacements of structures. The measurements were carried out using fixed reflectors on the elements of the bridge structure.

• Ground-based laser scanning (TLS): used to obtain three-dimensional information about the shape and position of structures. Point clouds obtained in different periods were compared for visualization and quantification of deformations **(Batilovic et al., 2024)**.

• Accuracy assessment: at each stage, the metrological characteristics of the measurements were evaluated, the standard deviations were calculated, and the consistency of the results between the methods was monitored. Additionally, a methodology for calculating precipitation and displacement based on the integration of GNSS, total station and TLS data has been developed **(Soilan et al., 2019)**. The development includes an algorithm for processing time series of measurements, a comparison of geometric parameters of structures for different eras of observations, as well as recommendations on the intervals of repeated measurements. The implementation of this geomonitoring system was implemented as part of a scientific project and used in the educational process of training specialists in the field of geodesy. The use of an integrated approach has allowed not only to improve the accuracy and reliability of observations, but also to create the basis for regular technical monitoring of similar facilities in earthquake-prone regions.

4 RESULTS AND DISCUSSION

Construction of interchanges, bridges, as well as construction of any other structures, requires the creation of a reference geodetic network. Using reference geodetic networks, the position of the centers of bridge supports and other elements of the bridge is determined and fixed, a detailed breakdown is made during the construction of supports and installation of span structures, and observations of deformations of structures are carried out. The geodetic network during bridge construction must be created in a single coordinate system and have increased accuracy in determining the coordinates of points. Geodetic network points that ensure the construction of a given object as a single structure must exist during the construction of the object. This requirement is not easy to fulfill, since during construction, some of the geodetic network points are destroyed or violated.

For monitoring by the Department of Mine Surveying and Geodesy SatbayevUniversity drafted a geodynamic testing area (GTA) project in 2020in the form of a GNSS network, where reference points are located considering the configuration of the observed objects (**Figure 3**). An important aspect in carrying out these works was the use of modern instruments and developed control tools for monitoring.

The main elements of the proposed geodetic network are:

First order network - is designed in the form of reference points (OP) of permanently operating geodetic base stations with reference to the State Geodetic Network (SGN) with a forced centering device (OP 1, OP2, OP 3, OP 4). The height of the points is taken to be not less than 1.5 m, to avoid obstacles to the passage of the radio signal.

The second-order network is designed in the form of points of the first-order satellite geodetic network (SGN) on the body of the observed objects.

Figure 3 – Layout of the support points of the transport interchange network.

Control points are laid along the street on the foundations of buildings and structures. Reflective and seismological marks, monitoring prisms and sedimentary marks are fixed on the controlled objects, along which further observations of deformations of buildings and structures are carried out, ensuring the necessary accuracy in accordance with the requirements of SP RK 3.06.07-86 «Bridges and pipes». Rules for surveys and tests and SP RK 1.03-26-2004 «Geodetic works in construction».

When monitoring the deformation of a transport interchange and high-rise buildings, a new design of geodetic points of forced centering (GPCC) was proposed as permanent supports, which meets the standards of regulatory literature **(Patent No. 35798)**, **(Patent No. 35898).** GPCC is a reinforced concrete pile, 12 meters long (**Figure 4**), installed in the selected location.

The stability control of the points can be easily performed by repeated measurements. The accuracy of determining the relative position of the starting points is increased by using the trilateration method.

When creating geodetic control points (GCPs), the following requirements must be met. The pile height must be approximately 1.3 m higher than the planned vertical layout of the landscaping,

with its installation in a vertical position using spacers and jack frames. A hole at least 3.2 m deep is drilled around a pile with a diameter of 0.6 m to install the casing pipe. In order to ensure the stability of the pile, the bottom of the hole must be tamped and filled with concrete approximately 50 mm thick. After this, a casing pipe approximately 0.5 m in diameter and 3 m long is installed on the concrete, so that the pile is in the center of this structure. To eliminate the influence of temperature and rainfall, a layer of ash and slag waste is placed on top, followed by the construction of formwork and a blind area. To ensure the installation of a geodetic device, a table measuring 0.2 × 0.2 m with a set screw is mounted on top of the pile. In order to ensure visibility from all directions, on each rectangular metal plates are installed on the side of the pile, to which reflective plates are glued **(Patent No. 35898)**.

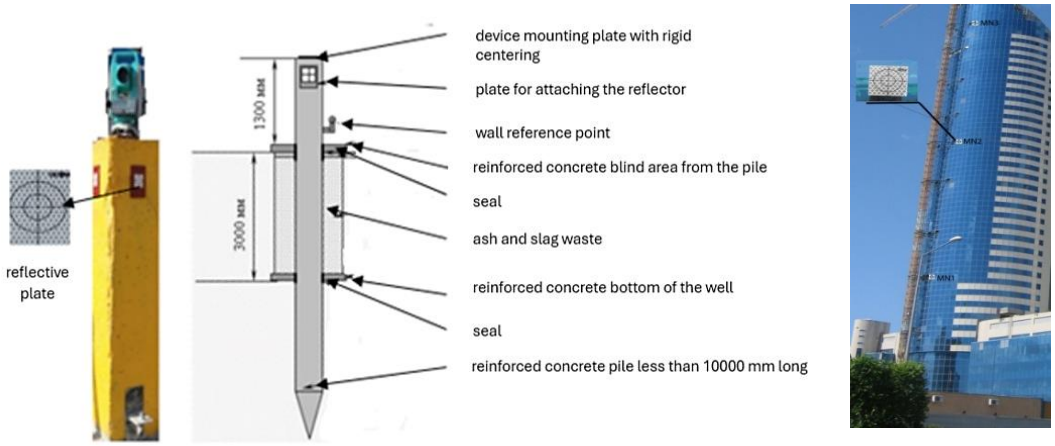


Figure 4 – Scheme of pile support point (a) and reflective observation marks (b).

The new device allows to increase the accuracy of centering, as well as the efficiency of measurements in the absence of tripods at the points of standing and observation. To obtain precise coordinates for the planned altitude justification of the network, it was decided to use GNSS equipment and satellite measurements that performed in static mode; work in this mode implies a conditional division into two stages, these are field work and office processing. The purpose of geodetic monitoring of industrial site structures is to ensure the reliability, safety and functional suitability of the structures in operation; analysis of the stress state, deformations and displacements of structures; observation of general deformations and cracks in individual elements of the structures in operation by conducting systematic observations and instrumental control.

When solving monitoring problems, all the most important engineering-geological and mining factors, the type and characteristics of the protected structures, and the requirements imposed on them were considered.

All work was carried out by the GPS system and for comparison of results the electronic tachometer TCR1201 from Leica Geosystem and the digital high-precision level DNA03 were used. Andlaser scanner. The coordinates of the geodetic base are defined in the local system, and the altitude coordinates are defined in the Baltic system.

The displacement of structures in the vertical plane (settlement) is determined by the geometric leveling method using a DNA 03 digital laser level and a digital invar rod. The determination of the roll of the bridge columns was carried out using coordinates using an electronic tacheometer. Based on the obtained values and increments of the coordinates of points located in the same vertical plane, the linear value of the roll was calculated using the formula:

$$L = \sqrt{(X_1 - X_2)^2 + (Y_1 - Y_2)^2}\ , \qquad (1)$$

where X1, X2, Y1, Y2 are the coordinates of the characteristic points of the structure in the lower and upper sections, respectively.

The determination of the eccentricity of the coaxiality of the circular bridge support was carried out from the points of the geodetic network, and the determination of the deflection of the bridge roof

beams was carried out using a digital high-precision level and a digital invar rod. To solve this problem, the rod was installed at the points of the beginning, middle and end of each beam span.

To determine the deflection, the magnitude of the deflection arrow $f_{абс}$ and relative deflection $f_{отн}$ calculated using the formulas:

$$f_{абс} = \frac{2Z_2 - (Z_1 + Z_3)}{2}; \quad (2)$$

$$f_{отн} = \frac{f_{абс}}{L}, \quad (3)$$

Where Z_1 And Z_3 - elevation marks of the extreme points of the building structure in the considered section of the straight line.

To determine the magnitude (Fig. 5) of the deflection $f_{абс}$ and relative deflection $f_{отн}$ calculated using the formulas:

$$f_{абс} = \frac{2Z_2 - (Z_1 + Z_3)}{2}; \quad (4)$$

$$f_{отн} = \frac{f_{абс}}{L}, \quad (5)$$

Where Z_1 And Z_3 - elevation marks of the extreme points of the building structure in the considered section of the straight line.

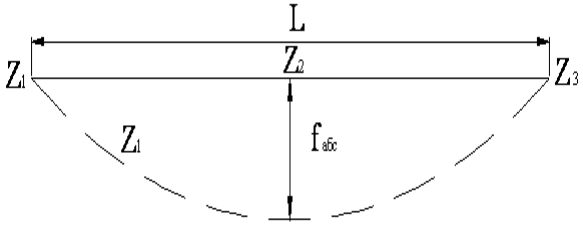


Figure 5-Geometric diagram of the deflection of floor beams.

The results obtained from the assessment of the technical condition of the structures using the above-described methodology were compared with the permissible values of SNiP - "Inspection and assessment of the technical condition of buildings and structures" Astana, 2015. The permissible value for the deflection of roof beams is 1/300 L, where L, m is the length of the beam. The permissible value of deviation of the columns of the enrichment plant structure is 15 mm, if the height is up to 4 meters.

5 CONCLUSIONS

Based on the research conducted by the authors:

1. A methodology for creating a support network for monitoring the deformation of bridges has been developed and geodetic monitoring of the transport interchange, as well as ground buildings, has been carried out.

2. The necessity of using satellite geodesy, electronic total stations and laser scanning methods for monitoring engineering structures is substantiated. For the installation of high-precision electronic and laser devices during geomonitoring of the earth's surface, the authors have developed a permanent forced centering point to ensure the speed and accuracy of centering, eliminating the use of tripods.

3. Methods for determining precipitation and displacement of structures are proposed. The research results were implemented during the implementation of a scientific project, as well as used in the educational process.

4. The novelty of the developed network and the design of the point are confirmed by the Certificates of the Republic of Kazakhstan for the product of science. The results obtained can be used to increase the level of industrial safety at other facilities and minimize the risks caused by the seismic activity in the area.

5.The creation of a monitoring network for high-precision observations of the condition of engineering structures using electronic and satellite GPS receivers has reduced the time spent on

determining coordinates in terms of one point being taken by 10-15 times and increased the accuracy of determining coordinates by at least 2 times.

Thus, the performed research has confirmed the effectiveness of an integrated approach to geodetic monitoring of the technical condition of engineering structures. The developed methodology can be recommended for use in similar engineering and geological conditions, and the results obtained can be used both in scientific and design and production practice.

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RESEARCH ARTICLE

A TECHNOLOGICAL APPROACH TO REDUCING LABOR AND MATERIAL CONSUMPTION OF CRANE RUNWAY I-BEAMS WITH CORRUGATED WEB

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Abstract. *The growing demand for industrial and logistics infrastructure has intensified the need for efficient and economically viable structural systems, particularly in crane runway applications. Welded I-beams with corrugated webs have emerged as a promising alternative to conventional flat-web designs, offering notable advantages in terms of production efficiency, weight reduction, and structural performance. This study investigates the technological strategies involved in manufacturing such beams, with a focus on minimizing labor intensity and material usage through process optimization. A comparative analysis is conducted between beams with flat and corrugated webs, drawing upon experimental data and practical observations from automated production lines. The research highlights the implementation of rotary corrugation machines, automated welding stations, and mechanized assembly platforms. A key innovation lies in eliminating transverse stiffeners, made possible by the enhanced out-of-plane stability provided by the corrugated profile. This not only reduces the number of fabrication steps but also contributes to overall simplification of the production workflow. The findings indicate that the use of corrugated webs results in a weight reduction of up to 6.9%, depending on the design load, and a decrease in labor intensity by up to 40% when compared to traditional flat-web I-beams. These improvements are achieved without compromising structural integrity or regulatory compliance. In conclusion, the study demonstrates that corrugated web beam technology is a viable solution for modern steel construction. It enhances productivity, lowers manufacturing costs, and supports broader adoption of efficient beam systems in industrial and civil engineering contexts.*

Keywords: *crane runway girders, corrugated web, welded I-beams, production technology, metal structures, automated welding, labor cost reduction.*

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ГОФРЛЕНГЕН ҚАБЫРҒАСЫ БАР ҚОСТАВРЛЫ КРАНАСТЫ АРҚАЛЫҚТАРДЫҢ ЕҢБЕК ЖӘНЕ МАТЕРИАЛ ШЫҒЫНЫН АЗАЙТУҒА БАҒЫТТАЛҒАН ТЕХНОЛОГИЯЛЫҚ ТӘСІЛІ

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Аңдатпа. *Индустриялық және логистикалық инфрақұрылымға деген сұраныстың артуы, әсіресе кран жолдары жүйелерінде, тиімді әрі экономикалық тұрғыдан негізделген көтергіш конструкцияларға деген қажеттілікті күшейтті. Гофрленген қабырғасы бар дәнекерленген қоставрлы кранасты арқалықтар дәстүрлі жазық қабырғалы балкаларға балама ретінде қарастырылады және өндірістік технологияны оңтайландыру, құрылымдық салмақты азайту және беріктікті арттыру тұрғысынан бірқатар артықшылықтарға ие. Осы зерттеуде мұндай арқалықтарды дайындауға арналған технологиялық тәсілдер қарастырылып, еңбек шығындары мен материалдық тұтынуды азайтуға бағытталған үдеріс тиімділігін арттыру жолдары талданады. Жазық және гофрленген қабырғалары бар кранасты арқалықтарға салыстырмалы талдау жүргізілді, ол автоматтандырылған өндірістік желілерден алынған эксперименттік деректер мен бақылауларға негізделген. Зерттеу барысында гофрлеуге арналған ротациялық машиналарды, автоматтандырылған дәнекерлеу жүйелерін және механикаландырылған жинақтау жабдықтарын қолданудың маңыздылығы атап көрсетіледі. Негізгі технологиялық артықшылық — гофрленген қабырғаның жоғары орнықтылығы арқасында көлденең қатаңдық элементтерінен бас тарту мүмкіндігі. Бұл өндірістік процесті едәуір жеңілдетіп, технологиялық операциялар санын қысқартуға ықпал етеді. Зерттеу нәтижелері көрсеткендей, гофрленген қабырғаны қолдану арқасында кранасты арқалықтың салмағы жүктеме түріне қарай 6,9 %-ға дейін, ал еңбек шығыны 40 %-ға дейін төмендейді. Бұл артықшылықтар құрылым сенімділігі мен нормативтік талаптарды сақтай отырып жүзеге асады. Қорытындылай келе, гофрленген қабырғалар технологиясын кранасты арқалықтарда қолдану қазіргі заманғы болат құрылысында өндіріс тиімділігін арттырудың, шығындарды төмендетудің және өнеркәсіптік пен азаматтық инженерияда қолдану аясын кеңейтудің тиімді жолы болып табылады.*

Түйін сөздер: *кранасты арқалықтар, гофрленген қабырға, дәнекерленген қоставр, өндіріс технологиясы, металл конструкциялар, автоматтандырылған дәнекерлеу, еңбек шығынын төмендету.*

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НАУЧНАЯ СТАТЬЯ

ТЕХНОЛОГИЧЕСКИЙ ПОДХОД К СНИЖЕНИЮ ТРУДОЗАТРАТ И МАТЕРИАЛОЁМКОСТИ ДВУТАВРОВЫХ ПОДКРАНОВЫХ БАЛОК С ГОФРИРОВАННОЙ СТЕНКОЙ

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Аннотация. *Рост потребности в индустриальной и логистической инфраструктуре увеличил спрос на эффективные и экономически обоснованные несущие конструкции, особенно в системах крановых конструкций. Сварные двутавровые подкрановые балки с гофрированной стенкой становятся перспективной альтернативой традиционным подкрановым балкам с плоской стенкой, демонстрируя преимущества в технологичности производства, снижении массы и повышении прочности. В настоящем исследовании рассматриваются технологические подходы к изготовлению таких балок с акцентом на сокращение трудозатрат и расхода материалов за счёт оптимизации процессов. Проведён сравнительный анализ подкрановых балок с плоской и гофрированной стенками на основе экспериментальных данных и наблюдений с автоматизированных производственных линий. В работе подчеркивается значение применения ротационных машин для гофрирования, автоматизированной сварки и механизированной сборки. Ключевое технологическое преимущество заключается в отказе от поперечных ребер жёсткости, благодаря повышенной устойчивости гофрированного профиля. Это существенно сокращает количество операций и упрощает производственный процесс. Результаты показывают, что использование гофрированной стенки позволяет уменьшить массу балки до 6,9 % (в зависимости от расчётной нагрузки), а трудоёмкость — до 40 % по сравнению с традиционными балками. Эти преимущества достигаются без ущерба для надёжности конструкции и соответствия нормативам. Таким образом, применение технологии гофрированных стенок в подкрановых балках представляет собой эффективное решение для современного строительства металлоконструкций, повышающее производительность, снижающее затраты и расширяющее возможности применения в промышленной и гражданской инженерии.*

Ключевые слова:. *подкрановые балки, гофрированная стенка, сварные двутавры, технология производства, металлические конструкции, автоматизированная сварка, снижение трудозатрат.*

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CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

АЛҒЫС / ҚАРЖЫЛАНДЫРУ КӨЗІ

Зерттеу өз қаражаты есебінен жүргізілді.

МҮДДЕЛЕР ҚАҚТЫҒЫСЫ

Авторлар мүдделер қақтығысы жоқ деп мәлімдейді.

БЛАГОДАРНОСТИ/ИСТОЧНИК ФИНАНСИРОВАНИЯ

Исследование проведено за счет собственных средств.

КОНФЛИКТ ИНТЕРЕСОВ

Авторы заявляют, что конфликта интересов нет.

1 INTRODUCTION

The increasing demand for industrial and civil infrastructure has led to the growing importance of optimizing structural components in steel-framed buildings. Among these, crane runway systems play a critical role in the operation of overhead lifting equipment and must ensure high reliability under variable and cyclic loads. A key factor influencing their performance is the stability of the beam web, particularly in I-section crane runway beams. When subjected to elastic-plastic deformation and potential overloads, the structural integrity of the web determines the overall energy absorption capacity of the system. Therefore, the search for optimal cross-sectional configurations is a crucial research direction in improving the resilience of steel frameworks.

Recent advances have shown that replacing traditional flat webs with corrugated ones can significantly enhance the buckling resistance of the web, even when using thinner steel plates. This structural improvement not only reduces the need for transverse stiffeners but also lowers material consumption and simplifies the manufacturing process. Despite these advantages, normative documents in Kazakhstan and abroad still lack clearly defined methods for the design and calculation of crane runway I-beams with corrugated webs. This creates a gap between practical needs and regulatory support, underlining the necessity of developing new approaches and adapted analytical tools for structural engineers.

Modern structural solutions in the field of light metal structures (LMS) aim to achieve high techno-economic performance by utilizing thin steel sheets and implementing mechanized or fully automated production lines. The comprehensive use of efficient LMS, automated manufacturing, large-block assembly, as well as high-strength steels and lightweight thermal insulation materials for enclosing structures, enables a significant increase in the pace of building and structure construction.

One of the promising directions in the field of load-bearing metal structures is the application of welded I-beams with thin corrugated webs. In Kazakhstan, construction systems such as "Alma-Ata" and "BGS-Kazakhstan" have been developed and applied in practice, including in roof and floor beams, as well as in columns of single-story and multi-story building frameworks. Based on extensive research and design studies, a range of standard profiles and regulatory documents has been developed to support the use of such systems, even in seismic zones. The importance of these developments is evidenced by the inclusion of corrugated-web I-beams in the Eurocode adaptations for Kazakhstan. Between 1981 and 2015, over 250 buildings were constructed using these beams, designed by the "Institute Proektstalkonstruktsiya" (Almaty), with long-term operational success.

The purpose of this study is to conduct a comprehensive analysis of the performance of welded I-section crane runway beams with corrugated webs under overhead crane loading, and to develop engineering-based methods for calculating their behavior, including optimization of the corrugation geometry (length, pitch, and depth).

2 LITERATURE REVIEW

A corrugated beam is a beam with flanges made of metal of various cross-sections and a transversely corrugated (bent) web. The corrugated webs of beams can have triangular, sinusoidal, trapezoidal, rectangular, and other profiles **(Misiek, 2021).** The flanges of such beams are made of rolled steel, shaped profiles, electric-welded pipes, or reinforced concrete elements. Beams with corrugated webs are widely used in many countries.

In recent years, crane runway girders have received increased attention due to the growing construction of industrial buildings. Their reliability, strength, and efficiency contribute to improving production and logistics processes, as well as ensuring safety when handling heavy loads. A crane runway girder is a load-bearing structure that supports the loads from the wheels of an overhead crane moving within a workshop. Additionally, as structural elements of the frame, crane girders help decouple columns from the frame plane, transfer longitudinal forces from braking and wind loads to vertical connections between columns, and mitigate the impact of seismic and other external factors, thereby improving the coordinated performance of the entire structure.

Several design solutions for crane runway girders with corrugated webs have been proposed in the literature **(Wei, 2015)**. The effectiveness of corrugated webs in welded I-beams has been studied from various perspectives, including load-bearing capacity, strength **(Hlal, 2024)**, stability, and

durability (Yuan, 2024). Methods for reinforcing crane girders(Sebastiao, 2023), stress-strain behavior (SSB), and their response to various impacts have also been analyzed (Kettler, 2023). The application of corrugated webs in box-section crane girders has been studied in (Wei, 2015).

In certain industrial building conditions, the use of crane runway girders with corrugated webs becomes necessary, as these significantly influence their strength and stability. Steel savings of up to 20% can be achieved through the use of thinner web plates compared to flat web girders, eliminating the need for stiffeners due to improved stability achieved by the corrugation folds, whose peaks extend beyond the web plane. However, apart from studies by (Wei, 2015) and (Bryantsev & Okanov, 2024), further research on girders with corrugated diaphragms and triangular web profiles remains limited (Bradford, 2002).

This study focuses on the analysis of the strength characteristics and optimization of corrugated web parameters in crane runway girders(Bryantsev, 2019), aiming to improve calculation methodologies and expand their application in construction (Bryantsev, 2019).

3 MATERIALS AND METHODS

The manufacturing process of crane runway girders includes the stages of preparation, assembly, and welding of structural elements. The technological operations differ depending on the type of girder web: flat or corrugated.

3.1. Manufacturing of a girder with a flat web

At the initial stage, the girder body, which includes the web and two flanges, is assembled in the fabrication area. After positioning the elements, they are fixed in place to prevent deformation. The girder body is then transferred to the welding section, where the web is welded to the flanges.

After completing this operation, the semi-finished product is returned to the assembly area for the installation of stiffeners, which are necessary to increase the load-bearing capacity of the structure. The stiffeners are installed with precise adherence to design dimensions and geometry (Bryantsev, 2024). The girder is then sent back to the welding section for the final welding of the stiffeners. This additional stage of assembly and welding increases the overall manufacturing time of the structure.

3.2. Manufacturing of a girder with a corrugated web

The manufacturing technology of a girder with a corrugated web has significant differences. After fabricating the main body, which consists of the corrugated web and two flanges, welding is performed as the first stage(Bryantsev, 2020).. Due to the structural advantages of the corrugated web, which provides stability and rigidity without the need for stiffeners, additional assembly and welding stages are not required. Once the end elements are welded, the structure is considered complete.

Thus, the manufacturing process of a girder with a corrugated web is characterized by lower labor intensity, resulting from the reduction of technological operations and fewer material transfers between workstations. This ensures time and resource savings in production (Shuryn, 2020).

A flat steel sheet is fed between two toothed rollers that rotate toward each other (Figure 1). A set of removable plates (teeth) of various sizes allows for adjusting the corrugation parameters. The experimental version of this machine confirmed the correctness of the selected corrugation method. When operated by a single worker, the machine was capable of corrugating sheets up to 1,600 mm in width and 8.0 mm in thickness at a speed of 10 to 12 m/min, which is three to four times faster than forming corrugations using press equipment (Ibrahim, 2006).

One of the advantages of this corrugation method is that the sheet maintains a constant cross-section along its entire length, whereas press-based corrugation may lead to local thinning of the sheet and significant changes in the steel's properties. Thanks to its compact dimensions, the machine was easily integrated into the main production line for girder fabrication. Additionally, the flexible technology developed on its basis fully addressed the issue of corrugated web production (Figure 2) and allowed for an annual production capacity increase of welded I-beams under the "Alma-Ata"

system from 10,000 to 12,000 tons, equivalent to the fabrication of 600,000 to 800,000 m² of roofing and flooring elements **(Kettler, 2021).**

The **Figure 1** illustrates the process of forming corrugations in a steel sheet using a rotary machine. The steel sheet passes between two rotating rollers, which are equipped with removable plates designed to shape the material into a corrugated profile. The upper and lower rollers rotate in opposite directions, gradually bending the sheet as it moves through the machine. The spacing between the rollers is adjustable, allowing for control over the depth and shape of the corrugations. This method ensures uniform deformation of the sheet while maintaining a consistent cross-section along its entire length, making it an efficient technique for manufacturing corrugated structural elements **(Kudryavtsev, 2021)**.

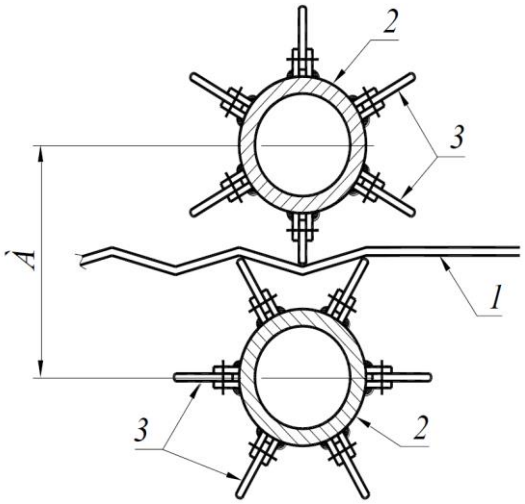

Figure 1 – Schematic diagram of steel sheet corrugation on a rotary machine.

Figure 2 – Corrugated webs in the assembly shop.

The comparative analysis of the manufacturing processes for flat-web and corrugated-web crane runway beams reveals a clear advantage in favor of the latter. The use of corrugated webs eliminates the need for transverse stiffeners, thereby reducing the number of fabrication steps and significantly lowering labor intensity. The integration of rotary corrugation machines into production lines further enhances efficiency by enabling faster, uniform, and more stable web formation without compromising steel properties. This streamlined approach results in time and cost savings, increases production capacity, and supports the widespread implementation of corrugated web technology in the fabrication of high-performance steel beams.

4 RESULTS AND DISCUSSION

The evaluation of cost-effectiveness and manufacturing efficiency plays a crucial role in assessing the practical advantages of using corrugated web I-beams in crane runway systems. To quantify these benefits, a detailed comparison was conducted between beams with flat and corrugated webs under various load conditions. The analysis includes structural weight distribution, material utilization, and labor intensity across key production stages. Graphical data and tabular results were used to illustrate the reductions in weight and complexity associated with the corrugated web configuration. This section presents the findings of the comparative study, supported by numerical and experimental observations, and highlights the economic and technological advantages that support the broader adoption of corrugated web technology in beam fabrication.

4.1. On Cost-Effectiveness

The factory cost of the structure consists of the cost of raw materials and manufacturing expenses. Calculation of the total weight of all crane runway girders for a 10-ton load

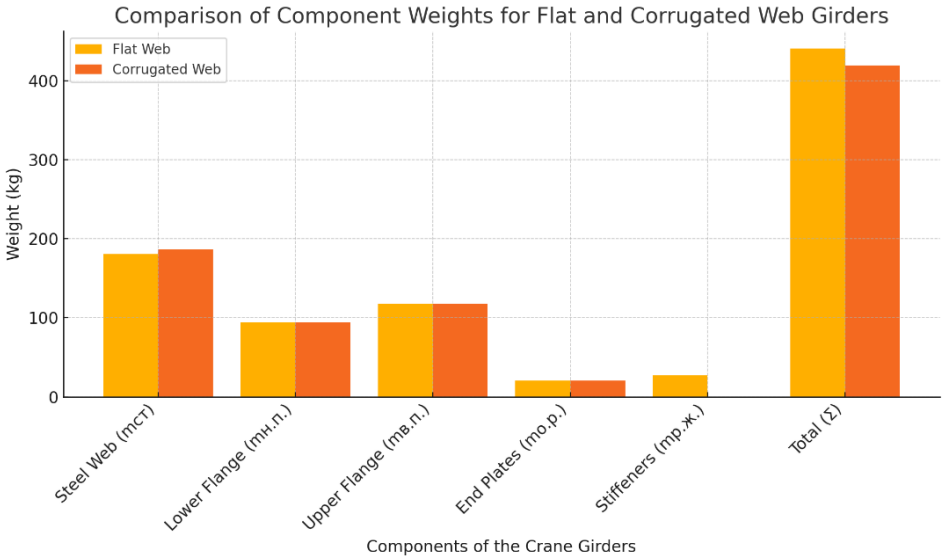

Figure 3 – Comparison of Component Weights for Flat and Corrugated Web Crane Girders (10t Load).

The Figure 3 illustrates the weight distribution of different components in crane runway girders with flat and corrugated webs. The comparison highlights that the total weight of the girder with a corrugated web is 4.9% lower than that of the girder with a flat web. This reduction is primarily achieved by eliminating the need for stiffeners while maintaining structural integrity. The use of a corrugated web allows for weight savings, leading to more efficient material utilization and reduced production costs.

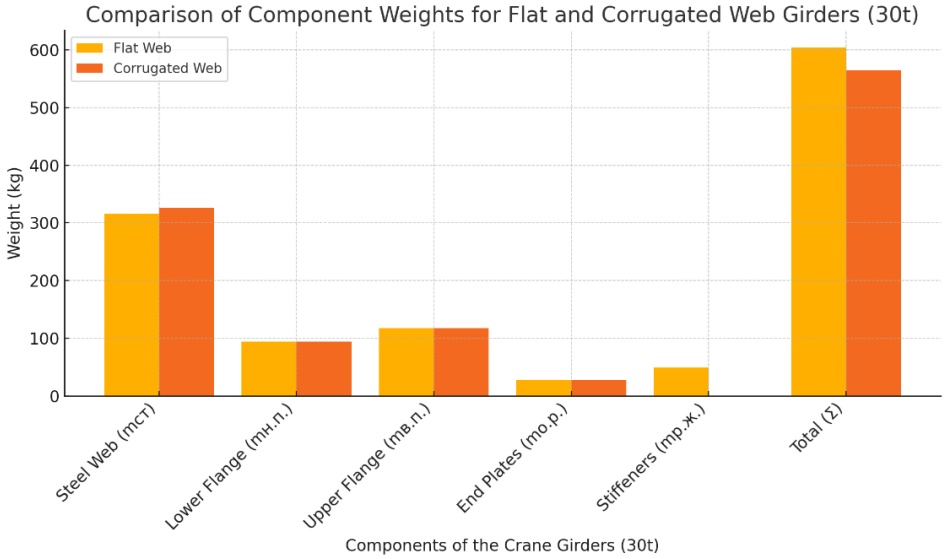

Figure 4 – Comparison of Component Weights for Flat and Corrugated Web Crane Girders (30t Load).

The Figure 4 compares the weight distribution of different components in crane runway girders with flat and corrugated webs for a 30-ton load. The results show that the total weight of the girder with a corrugated web is 6.5% lower than that of the flat web girder. This reduction is achieved by eliminating stiffeners while maintaining structural stability, leading to improved material efficiency and reduced manufacturing costs.

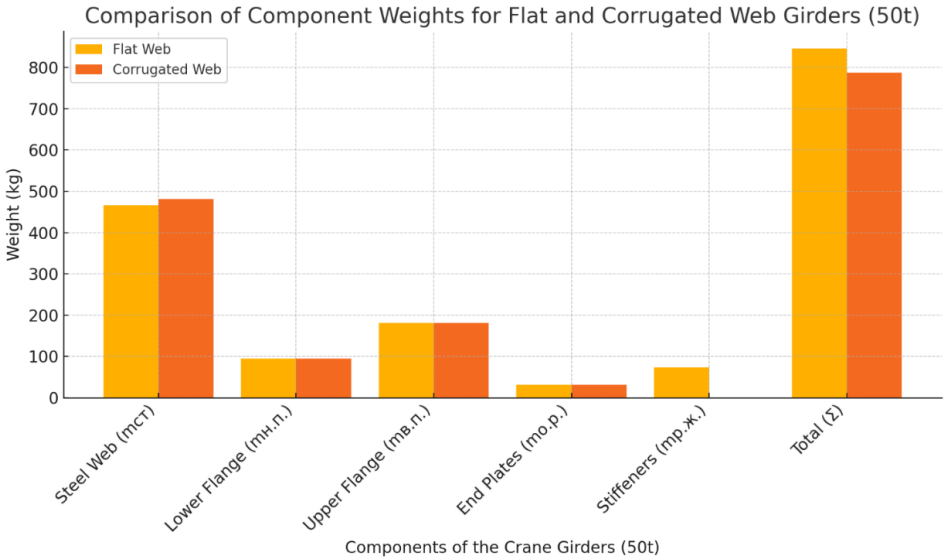

Figure 5 – Comparison of Component Weights for Flat and Corrugated Web Crane Girders (50t Load).

The Figure 5 compares the weight distribution of different components in 50-ton crane runway girders with flat and corrugated webs. The results demonstrate that the total weight of the girder with a corrugated web is 6.9% lower than that of the flat web girder. This weight reduction is primarily achieved by eliminating stiffeners while maintaining the necessary structural integrity. The use of a corrugated web improves material efficiency, reduces production costs, and simplifies the manufacturing process.

4.2. Labor Intensity

Since 1989, second-generation rotary-type machines have been installed in the republic's manufacturing facilities, capable of corrugating sheets up to 1950 mm in width and 12.0 mm in thickness at a processing speed of 8 to 10 m/min (Figure 6). The labor intensity of fabricating girders with corrugated webs accounts for 83% of that required for manufacturing thin-walled girders without stiffeners and 60% to 74% of that for thin-walled girders with stiffeners. This reduction in labor intensity is attributed to:

- Standardization of corrugation parameters and flange cross-sections, optimizing the manufacturing process;
- Minimization of the number of assembly components, reducing material handling and assembly complexity;
- Extensive use of single-sided flange welds, which simplifies the welding process and enhances efficiency;
- Elimination of transverse stiffeners, reducing the need for additional manufacturing steps;
- High productivity of advanced corrugation equipment, allowing for increased output with reduced processing time;
- Implementation of automated assembly of welded I-sections on mechanized stands with hydraulic fixation of section components (web and flanges), followed by integration into a unified girder element (Figure 7). Alternatively, inventory stands at production facilities can be utilized, depending on the production volume and the availability of specialized equipment;
- Mechanization and automation of the flange welding process, improving efficiency and reducing manual labor.

The adoption of these technological advancements has resulted in a significant decrease in production time and labor costs, enhancing the overall efficiency of manufacturing girders with corrugated webs.

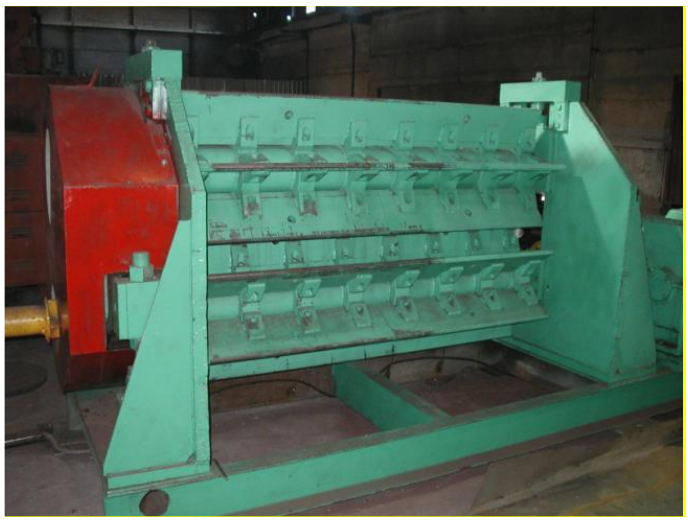

Figure 6 – Rotary Machine for Continuous Corrugation of Steel Sheets.

The machine is designed for the continuous corrugation of steel sheets with a maximum width of 1950 mm and a maximum thickness of 12.0 mm.

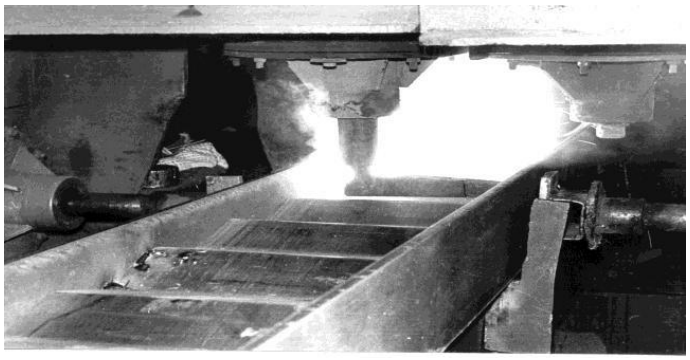

Figure 7 – Assembly of Welded I-Beams with Corrugated Webs in Mechanized Production Areas.

To address these challenges, relevant developments have been carried out to improve the technological processes for manufacturing welded I-beams with corrugated webs. In particular, a specialized device has been designed for the production of girders with corrugated webs, with a projected capacity of up to 10,000 tons of metal structures per year. Given its compact dimensions, this equipment can be integrated into one of the modular buildings of the "Alma-Ata" type, ensuring efficient and scalable production.

Relevant efforts have also been undertaken to implement automated submerged arc welding (SAW) for the flange joints of BGS beams, utilizing a serial welding machine with adjustable wire feed speed, ADF-1202 **(Figure 8)**.

Subsequently, similar work was carried out to automate the welding of flange plates in a carbon dioxide environment and in a mixed gas environment with argon **(Figure 9)**.

The welding quality in both methods complies with the requirements of regulatory documents.

Since the web thickness typically ranges from 3.0 mm to 5.0 mm, the flange welds are usually performed from one side. However, when welding thicker webs, double-sided welding is applied, with the beam positioned optimally for the welding process. The fillet weld sizes are either made equal or welded with unequal fillets to meet the regulatory requirements for fillet dimensions depending on the thickness of the welded components.

After attaching various fastening elements to the beam using semi-automatic or manual welding, the structure undergoes anti-corrosion treatment in a specialized sandblasting chamber. Subsequently, the metal structure is primed once and dried in a drying chamber. **Figure 10** presents

a welded I-beam of the "BGS-Kazakhstan" system, fully treated with anti-corrosion protection and ready for delivery to the customer.

Figure 8 – Universal Steel Coils for I-Beam Webs.

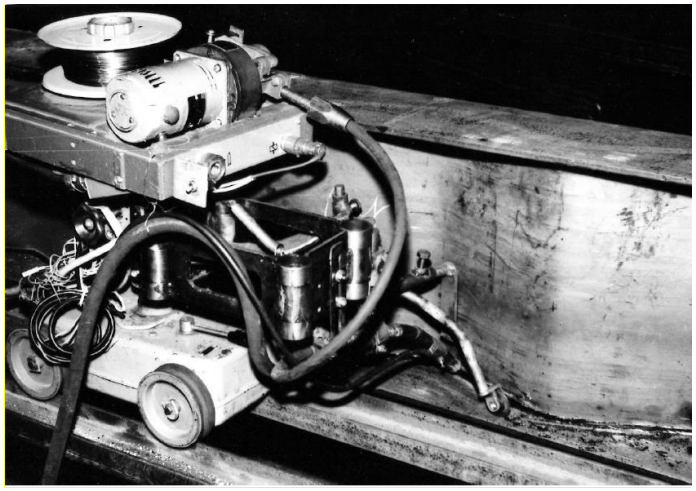

Figure 9 – 1985. Serial Welding Tractor with a Device for Welding Flanges of Beams with Corrugated Webs.

Figure 10 – Positioning of a Welded I-Beam Profile with a Corrugated Web on a Rotator for Welding Flange Joints with Unequal Fillets.

The **table 1** provides a comparative analysis of labor intensity for different beam types, including corrugated web beams, beams without stiffeners, and beams with stiffeners. The data

illustrate that beams with corrugated webs require the least labor effort across all manufacturing stages, making them the most efficient option in terms of production complexity and cost.

Table 1
Labor Intensity of Structure Manufacturing

Operation	Beam with Corrugated Web		Beam without Stiffeners		Beam with Stiffeners	
	Units of Measurement	%	Units of Measurement	%	Units of Measurement	%
Preparation and Transportation	7,5	100	8,1	108	7,9	104
Processing and Component Fabrication	6,2	100	6,8	110	8,5	137
Assembly	3,5	100	3,5	100	4,4	126
Welding	3,2	100	5,9	184	7,9	247
Finishing, Painting, and Loading	6,0	100	7,3	122	6,9	115
Total	26,4	100	31,6	120	35,5	134

Among the key differences, welding stands out as the most labor-intensive stage, particularly for beams with stiffeners, where additional reinforcement significantly increases workload. Processing and fabrication also demand considerably more effort for beams with stiffeners due to the complexity of additional structural elements. While preparation, transportation, and assembly efforts remain relatively similar across all beam types, the finishing and painting process requires slightly more effort for beams without stiffeners.

Overall, corrugated web beams demonstrate the lowest total labor intensity, reducing welding and processing complexity. This suggests that using corrugated web beams can enhance manufacturing efficiency by streamlining production while maintaining structural integrity.

5 CONCLUSIONS

Based on the conducted research, the following specific conclusions are drawn in accordance with the stated objectives:

1. Corrugated web I-beams have demonstrated considerable potential for use in crane runway systems, particularly those subjected to dynamic and cyclic loading. The triangular corrugation profile enhances the out-of-plane stability of the web, thereby significantly increasing the beam's resistance to local and global buckling. This structural improvement makes it possible to eliminate the need for transverse stiffeners, which are typically used in flat-web beams to prevent buckling. As a result, the overall beam geometry becomes more efficient, lighter, and simpler to fabricate, without compromising structural safety or service performance.

2. The comparative weight analysis of flat versus corrugated web beams under various crane load scenarios (10t, 30t, 50t) showed a consistent and measurable reduction in the total weight of the structure – ranging from 4.9% to 6.9%. This weight reduction is directly attributed to the elimination of stiffeners and the optimized load distribution across the corrugated web. Lower beam weight contributes not only to material savings but also to easier transportation, reduced installation efforts, and potential savings in foundation costs due to lighter loads.

3. The production of beams with corrugated webs requires significantly less labor compared to beams with flat webs and stiffeners. This is due to the reduction in the number of assembly components, fewer welding seams, and minimal repositioning between technological stations. The analysis revealed that labor intensity can be reduced by approximately 20%–40%, depending on the specific design and beam configuration. This makes the use of corrugated webs a highly practical solution in terms of production efficiency and industrial scalability.

4. The introduction of second-generation rotary corrugation machines and mechanized welding stands into beam production lines has led to substantial improvements in output quality and consistency. These systems allow for the continuous, high-speed formation of corrugations in steel sheets while preserving uniform thickness and material properties. When combined with automated

welding technologies, the result is a streamlined manufacturing process that reduces fabrication time, minimizes human error, and enhances structural integrity.

5. The study strongly supports the application of triangular corrugation profiles with standardized geometric parameters – specifically in terms of corrugation pitch, depth, and wall thickness. Through numerical modeling and experimental validation, these parameters were found to significantly influence the stiffness, load-bearing capacity, and deformation characteristics of the beam. The research also highlights the importance of considering web eccentricity and localized stress concentrations in design, recommending their inclusion in future engineering calculation methodologies and national code provisions.

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RESEARCH ARTICLE

EXPANDED CLAY LIGHTWEIGHT CONCRETE TO INCREASE THE SEISMIC RESISTANCE OF BRICK BUILDINGS

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Abstract. *Development lightweight concrete production is particular importance for Kazakhstan and for its southern regions due to their high seismicity. In these conditions, reducing weight individual structures, buildings and structures whole through use lightweight expanded clay concrete can be considered one measures to increase their seismic resistance. Lightweight concrete two-layer walls with 6-8 cm thick layer structural concrete effective in seismic-resistant construction or in presence subsidence soils. Results SEM were used in studies to determine morphological structural features bulk studied bentonite clays. Important characteristic clay raw materials fire and air shrinkage, which means decrease in linear dimensions and volume clay sample during its drying. For studied clay, value air linear shrinkage under slow natural drying conditions 10.8%, under harsh artificial drying regime 7.8%. Fire shrinkage during firing samples $T=950^0C$ - 5.5%. With introduction 0.5% tire production waste powder into mass, expanded clay with bulk density less than 400 kg/m^3 can be obtained already temperature 1120^0C. Granules fired at 1160^0C have bulk density 0.484 g/cm^3 - bulk density expanded clay 280 kg/m^3 with closed porosity 77%. Presented results indicate that tire production waste is best additive for production expanded clay from clays in lightweight concrete technology in order to improve seismic resistance brick buildings. It was found that addition tire production waste to clays serves good intensifier swelling. It was confirmed that optimal additive tire production waste is 0.5-1% clay mass. Optimum firing temperature for expanded clay was determined to be $1120^0C \pm 20^0C$.*

Keywords: *bentonite clays, tire waste, expanded clay, swelling, seismic resistance*

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ҒЫЛЫМИ МАҚАЛА

КІРПІШ ҒИМАРАТТАРДЫҢ СЕЙСМИКАЛЫҚ ТӨЗІМДІЛІГІН АРТТЫРУ ҮШІН КЕРАМЗИТТІ ЖЕҢІЛ БЕТОН

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Аңдатпа. *Жеңіл бетон өндірісін дамытудың Қазақстан үшін, әсіресе, сейсмикалық жоғары болуына байланысты оның оңтүстік аймақтары үшін маңызы ерекше. Осы жағдайларда жеңіл керамзит бетонды қолдану арқылы жекелеген құрылымдардың, сондай-ақ жалпы ғимараттар мен құрылыстардың салмағын азайтуды олардың сейсмикалық төзімділігін арттыру шараларының бірі ретінде қарастыруға болады. Құрылымдық бетонның қалыңдығы 6-8 см қабаты бар жеңіл бетонды екі қабатты қабырғалар сейсмикалық төзімді құрылыста немесе шөгу топырақтары болған кезде тиімді. Зерттелетін бентонит саздарының негізгі бөлігінің морфологиялық құрылымдық ерекшеліктерін анықтау үшін зерттеулерде сканерлеуші электронды микроскоптың нәтижелері пайдаланылды. Саздың шикізаттың маңызды сипаттамасы от пен ауаның шөгуі болып табылады, бұл оны кептіру кезінде саз үлгісінің сызықтық өлшемдері мен көлемінің төмендеуін білдіреді. Зерттелетін саз үшін баяу табиғи кептіру жағдайында ауаның сызықтық шөгуінің мәні 10,8%, ал қатал жасанды кептіру режимінде - 7,8% құрайды. Үлгілерді күйдіру кезінде 950^{0}С температурада өрттің шөгуі 5,5% құрайды. Массаға шина өндірісінің қалдық ұнтағының 0,5% енгізген кезде 1120^{0}С температурада көлемді тығыздығы 400 кг/м^3-тен аз керамзит алуға болады. 1160^{0}С күйдірілген түйіршіктердің көлемдік тығыздығы 0,484 г/см^3, бұл 77% жабық кеуектілігімен шамамен 280 кг/м^3 керамзиттің көлемдік тығыздығына сәйкес келеді. Ұсынылған нәтижелер шина өндірісінің қалдықтары кірпіш ғимараттардың сейсмикалық төзімділігін арттыру мақсатында жеңіл бетон технологиясында бентонит саздарынан керамзит өндіру үшін ең жақсы қоспа болып табылатынын көрсетеді. Бентонит саздарына шина өндірісінің қалдықтарын қосу ісінуді жақсы күшейтетіні анықталды. Шина өндірісінің қалдықтарының оңтайлы қоспасы балшық массасының 0,5-1% құрайтыны расталды. Керамзит үшін оңтайлы күйдіру температурасы 1120^{0}С ± 20^{0}С болып анықталды.*

Түйін сөздер: *бентонит саздары, шина қалдықтары, керамзит, ісіну, сейсмикалық төзімділік*

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НАУЧНАЯ СТАТЬЯ

КЕРАМЗИТОВЫЙ ЛЕГКИЙ БЕТОН ДЛЯ ПОВЫШЕНИЯ СЕЙСМОСТОЙКОСТИ КИРПИЧНЫХ ЗДАНИЙ

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Аннотация. *Развитие производства легких бетонов приобретает особое значение для Казахстана и, в частности, для его южных районов в связи с высокой их сейсмичностью. В этих условиях снижение веса отдельных конструкций, а также зданий и сооружений в целом за счет применения легких бетонов из керамзита может рассматриваться как одна из мер повышения их сейсмостойкости. Легкобетонные двухслойные стены со слоем конструктивного бетона толщиной 6-8 см эффективны в условиях сейсмостойкого строительства или при наличии просадочных грунтов. В исследованиях были использованы результаты сканирующего электронного микроскопа для определения морфологических структурных особенностей основной массы исследуемых бентонитовых глин. Важной характеристикой глинистого сырья является огневая и воздушная усадки, что означает уменьшение линейных размеров и объема глинистого образца при его сушке. Для исследуемой глины величина воздушной линейной усадки в условиях медленной естественной сушки составляет 10,8%, а при жестком режиме искусственной сушки – 7,8%. Огневая усадка при обжиге образцов на температуру 950^{0}С составляет 5,5%. При введении в состав массы 0,5% порошка отходов шинного производства керамзит с насыпной плотностью менее 400 кг/м^3 может быть получен уже при температуре 1120^{0}С. Гранулы, обожженные при 1160^{0}С, имеют объемную массу 0,484 г/см^3, что соответствует насыпной массе керамзитов около 280 кг/м^3 с закрытой пористостью – 77%. Приведенные результаты свидетельствуют о том, что отходы шинного производства являются лучшей добавкой для производства керамзита из бентонитовых глин в технологии легких бетонов с целью повышения сейсмостойкости кирпичных зданий. Установлено, что добавка отходов шинного производства в бентонитовые глины служат хорошим интенсификатором вспучивания. Подтверждено, что оптимальная добавка отходов шинного производства равна 0,5-1% от массы глины. Определена оптимальная температура обжига керамзита 1120^{0}С ± 20^{0}С.*

Ключевые слова:. *бентонитовые глины, отходы шин, керамзит, вспучиваемость, сейсмостойкость*

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CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

АЛҒЫС/ҚАРЖЫЛАНДЫРУ КӨЗІ

Зерттеу жеке қаржыландыру көздерін пайдалана отырып жүргізілді.

МҮДДЕЛЕР ҚАҚТЫҒЫСЫ

Авторлар мүдделер қақтығысы жоқ деп мәлімдейді.

БЛАГОДАРНОСТИ/ИСТОЧНИК ФИНАНСИРОВАНИЯ

Исследование проводилось с использованием частных источников финансирования.

КОНФЛИКТ ИНТЕРЕСОВ

Авторы заявляют, что конфликта интересов нет.

1 INTRODUCTION

Following effective seismic codes, common buildings are considered to be made of the same material throughout the story distribution and based on an ideal rigid soil. However, in daily construction practice, there are often cases of buildings formed by a bottom part constructed with reinforced concrete (r/c) and a higher steel part, despite this construction type not being recognized by code assumptions. In addition, soil deformability, commonly referred to as the Soil-Structure Interaction (SSI), is widely found to affect the earthquake response of typical residence structures, apart from special structures, though it is not included in the normative design procedure (**Askouni, 2024**). The normative common building seismic design mainly involves the same structural material throughout the entire building, which rests on ideal rigid supporting soil, following the rules of (**EN 1992-1-1; EN 1993-1-1; EN 1998-5**). The described mixed-in-height structures can be seen in daily construction cases related to projects based on renovating, redesigning, or updating the structural function of buildings.

The current large-scale transition to industrial-innovative development of the construction industry requires the use of lightweight concrete on porous aggregates with low thermal conductivity, sufficient mechanical strength and low density. One of such aggregates, which can be widely used in industry, are insulating expanded claystones based on local bentonite clays. The forecast reserves of bentonite clays only in the Turkestan region are about 160 million tonnes, and in Kazakhstan are more than 10 billion tonnes, in order to obtain from them heat-insulating expanded clay are not yet fully assessed, although they are very interesting and their prospects are obvious in the transition of the Republic of Kazakhstan to a ‘green’ economy to implement the concept of its second direction - energy efficiency of housing and communal services. Prospects of mass purposeful industrial use of bentonite clays for production of expanded clay in the technology of lightweight concrete in order to increase the earthquake resistance of brick buildings are not yet fully assessed, although they are very interesting and their prospects are obvious. The pace of construction in Kazakhstan is increasing year by year, but new apartment buildings with load-bearing brick walls have almost ceased to be commissioned. The main reasons for this are the high estimated cost and duration of construction, so the strong, durable and environmentally friendly brick houses have been replaced by quickly erected panel houses, as well as buildings with a monolithic reinforced concrete frame, in which bricks or other wall materials are used only for the construction of self-supporting walls and partitions. Most of the modern residential buildings with load-bearing brick walls were built in the second half of the 20th century. Today, almost all of these houses require major repairs and seismic testing. The development of lightweight concrete production is of particular importance for Kazakhstan and, in particular, for its southern regions due to their high seismicity. In these conditions the reduction of weight of separate constructions, and also buildings and constructions as a whole at the expense of application of light concretes from expanded clay can be considered as one of measures of increase of their seismic resistance. Lightweight concrete two-layer walls with a layer of structural concrete 6-8 cm thick are effective in conditions of earthquake-resistant construction or in the presence of subsidence soils (**Zhakipbayev et al., 2021**).

Tire production for vehicles is increasing exponentially given the rapidly growing population and transportation development. Substantial rubber waste is produced from waste tires past their service time. Tire waste is nearly proportional to tire production given that the world’s yearly tire production exceeded 2.9 billion tires in 2017. This massive amount of non-biodegradable waste occupies a large area and causes environmental hazards. Burning or using tire as fuel may produce toxic gases that are harmful for environment and may cause destructive pollution of natural air. Tire rubber contains styrene, a strongly toxic component that is highly damaging to humans. Therefore, dumping of waste tires may be very dangerous to human health. Recycling of waste in any way is beneficial. In recent years, researchers have attempted to establish a proper guideline for recycling tire waste in different ways. The global tire recycling market was valued at USD 0.95 billion in

2016 and is expected to grow at a compound annual growth rate of 2.1% during the forecast period. The same report revealed that North America accounts for approximately 31% of the revenue share of the global tire recycling market. In response to the growing environmental concerns, waste tires are now being recycled in a manner that not only benefits the environment but also contributes to economic growth. The energy recovered from waste tires also contribute to the economy of industries in developed countries. Around 6% to 8% of waste tires are being recycled as civil engineering materials in the US and in EU countries, but only around 0.4% of waste tires are being recycled in Australia. Concrete is the most used construction material in the world. Optimizing the cost while maximizing the strength and durability of concrete along with improving the greenness of concrete construction are current global challenges. This issue requires advanced materials that can replace the traditional components of concrete. Given the good strength, ductility, and strain control properties of tire waste, it may be utilized as a substitute for concrete components. Rubber can be applied to concrete and mortar by replacing fine aggregates (FA) and coarse aggregates (CA) or used as binder. The advantages of incorporating crumb rubber (CR) into any engineering cementitious composite (ECC) include lowering the CO_2 emissions and increasing the greenness of the environment. Accumulation of waste is subsequently increased to hazardous levels. Tire waste is one of them that cause serious environmental issues because of the rapid rise in and numerous variations of modern developments worldwide. Thus, recycling waste tire rubber in the form of aggregates as supplementary construction material is advantageous. Inclusion of recycled rubber aggregate (RA) lightens concrete, increases its fatigue life and toughness, advances its dynamic properties, and improves its ductility. Concrete with recycled RA performs well in hot and cold weather and achieved significant results under critical exposure and various loading conditions. Though RuC possesses low mechanical strength in general, specific treatment and additives inclusion can be a good solution to improve those properties reliably (**Gerges et al., 2018; Siddika et al., 2019**).

2 LITERATURE REVIEW

Concrete structures are prone to earthquake due to mass of the structures. The primary use of structural lightweight concrete (SLWC) is to reduce the dead load of a concrete structure, which allows the structural designer to reduce the size of the structural members like beam, column, and footings which results in reduction of earthquake forces on the structure. This paper attempts to predict the seismic response of a six-storied reinforced concrete frame with the use of lightweight concrete. A well-designed six-storey example is taken for study. The structure is modelled with standard software, and analysis is carried out with normal weight and lightweight concrete. Bending moments and shear forces are considered for both NWC and LWC, and it is observed that bending moments and shear forces are reduced to 15 and 20 percent, respectively, in LWC. The density difference observed was 28% lower when compared NWC to LWC. Assuming that the section and reinforcements are not revised due to use of LWC, one can expect large margin over and above MCE (maximum considered earthquake; IS 1893-2016), which is a desirable seismic resistance feature in important structures (**Vandanapu et al., 2018**).

The use of masonry infilled frames is very common for most types of building, accordingly state of the art of masonry infilled frame behaviour in general is known but there is still no suggestion of regulations on how to model or use it properly in structural analysis. The use of neural networks in the civil engineering field is already approved however the application of neural networks for the prediction of infilled frame behaviour is rare. There are only a few studies that have explored this topic. With a lack of available data from experiments of masonry infilled frames and with the uncertainty of numerical modelling, this research area needs to be further investigated. In order to connect most of the previously published data with new valuable conclusions, an experimental database of masonry infilled frames was collected. It was limited to only one-storey, one-bay infilled frames according to the availability and uniformity of the structural type (**Cascardi et al., 2017; Kalman Šipoš et al., 2019**).

The existing non-ductile RC structures built prior to the 1960s–1970s were mainly conceived to carry only vertical loads. As a result, the columns of these structures demonstrate poor overall hysteresis behavior during strong earthquakes, dominated by brittle shear or/and premature excessive slipping of the inadequately lap-spliced reinforcement. The poor overall hysteresis performance of existing RC structures built in the 1960s-1970s or earlier is invariably highlighted in the aftermath of every moderate-to-strong seismic event worldwide. Meanwhile, the catastrophic partial or/and general collapse of these structures, which form the majority of the building stoke in most countries, is extremely common, with immense social and economic impact (**Kalogeropoulos et al., 2019; Kalogeropoulos et al., 2021**).

Lightweight aggregate concrete is an innovative building material used to reduce the self-weight of a high-rise building. Recently, the use of lightweight aggregate in construction is increasing immensely due to its performance during an earthquake. Lightweight aggregate concrete (LWAC) is a solution for the achievement of sustainability in the construction sector, which helps us cut down the overall cost of a project in massive construction work (tall buildings and bridges). Additionally, using various industrial by-products and waste instead of natural aggregate allows us to reduce the negative impact on the environment. The development of lightweight aggregate concrete with its relevance is still prominent. The performance of lightweight aggregate on various properties of concrete is explored in this study. This study shows that the lightweight aggregate and waste materials of less density can be used for structural applications with a strength equivalent to that of normal weight concrete. The application and advantages of LWAC are also discussed in this study. The paper's overall finding reveals that LWAC can be used in sustainable construction growth and reduce waste by using it as natural aggregate in concrete to maintain environmental sustainability (**De Risi et al., 2018; Agrawal et al., 2021; Bagnoli et al., 2021**).

The current research presents a novel and sustainable load-bearing system utilizing cellular lightweight concrete block masonry walls. These blocks, known for their eco-friendly properties and increasing popularity in the construction industry, have been studied extensively for their physical and mechanical characteristics. However, this study aims to expand upon previous research by examining the seismic performance of these walls in a seismically active region, where cellular lightweight concrete block usage is emerging. The study includes the construction and testing of multiple masonry prisms, wallets, and full-scale walls using a quasi-static reverse cyclic loading protocol. The behavior of the walls is analyzed and compared in terms of various parameters such as force–deformation curve, energy dissipation, stiffness degradation, deformation ductility factor, response modification factor, and seismic performance levels, as well as rocking, in-plane sliding, and out-of-plane movement. The results indicate that the use of confining elements significantly improves the lateral load capacity, elastic stiffness, and displacement ductility factor of the confined masonry wall in comparison to an unreinforced masonry wall by 102%, 66.67%, and 5.3%, respectively. Overall, the study concludes that the inclusion of confining elements enhances the seismic performance of the confined masonry wall under lateral loading (**Chourasia et al., 2020; Zade et al., 2021; Khan et al., 2023**).

3 MATERIALS AND METHODS

Expanded clay is an environmentally friendly heat-insulating material, which are light porous materials of cellular structure in the form of ceramic granules obtained by firing bentonite clay, capable of swelling when quickly heated to a temperature of 1050-1300^{0}C for 25-45 minutes.

Firstly, the bentonite clays were selected and then ground in an ML-1r ball mill in an amount of 10 kg with passing through a shaker with a sieve at the bottom of 1 mm, followed by drying in a desiccator at 30^{0}C.

Prepared in advance and weighed for further experiments, the studied clay together with additives was mixed in an ALS-5 mixer in a dry state, gradually moistening with water until a paste-like consistency was obtained. The mass moistened in this way was kept for 4 hours and then mixed again. Pressed tablets were moulded from the prepared mass by packing method using a

hydraulic press PGM-100MG4A, with subsequent drying of the already pressed tablets at a temperature of 100-140^{0}C.

An important characteristic of clay raw materials is fire and air shrinkage, which means the reduction of linear dimensions and volume of the clay sample during its drying. For the studied clay, the value of air linear shrinkage under conditions of slow natural drying is 10.8%, and under severe artificial drying regime - 7.8%. Fire shrinkage when firing the samples at a temperature of 950^{0}C is 5.5%.

The suitability of various clay rocks as raw materials for expanded clay production is determined by their degree of swelling during firing and density of c expanded clay.

Temperature and time regime of thermal preparation of expanded expanded clay in laboratory conditions is presented in **Table 1.**

Table 1
Temperature and time regime of thermal preparation of expanded clay

Stages of synthesis	T, ^{0}C	Burning time, min
		normal mode
Heating in a drying oven	130	5
Thermal preparation	300	2
Raising the temperature in the furnace	1080-1180	23
Tempering at burning temperature	1080-1180	7
1st cooling stage	900-950	0,5-1
2nd cooling stage	30	7

Thermal preparation of samples was carried out in a muffle furnace, where the samples were heated for 2 minutes to 280-300^{0}C. After thermal preparation, the samples were fired at 1080-1180^{0}C with a temperature rise rate of 10-15^{0}C per minute.

The increase in the volume of raw materials during firing is estimated by the bloating coefficient, which expresses the ratio of the volume of expanded clay to the volume of the initial dry raw material.

According to the swelling coefficient, clay raw materials are divided into weakly swelling (Csw < 2.5), medium swelling (Csw = 2.5-4.5), well swelling (Csw > 4.5).

4 RESULTS AND DISCUSSIONS

According to the data of electron microscopy and X-ray energy-dispersive microanalysis (**Figure 1**), performed at the Department of Silicate and Nanomaterials Technology of the Institute of Physics and High Technologies of the National Research Tomsk Polytechnic University on a scanning electron microscope SEM JEOL JCM-6000 together with the Center for Physic-chemical Research Methods "Laboratory of Electron Microscopy" of the Belarusian State Technological University on a scanning electron microscope SEM JEOL JSM-5610LV at magnifications (x100–x1000), we found that the morphological structural features of the bulk of the studied bentonite clays are represented by microaggregates of a complex structure, consisting of sheet-like associations, forming isometric and slightly elongated ultramicroaggregates, in which clay particles contact each other with basal planes.

Bentonite clays, at swelling temperatures, consist of a crystalline phase, mainly consisting of silica and alumina, the amount of which during the swelling process continuously decreases by 50-70% at the beginning and 1-10% at the end; a liquid phase, consisting of fusible components transferred to the melt and some silica and alumina, the amount of which reaches 90% and higher by the end of the swelling process; and a gaseous phase, varying in composition and amount.

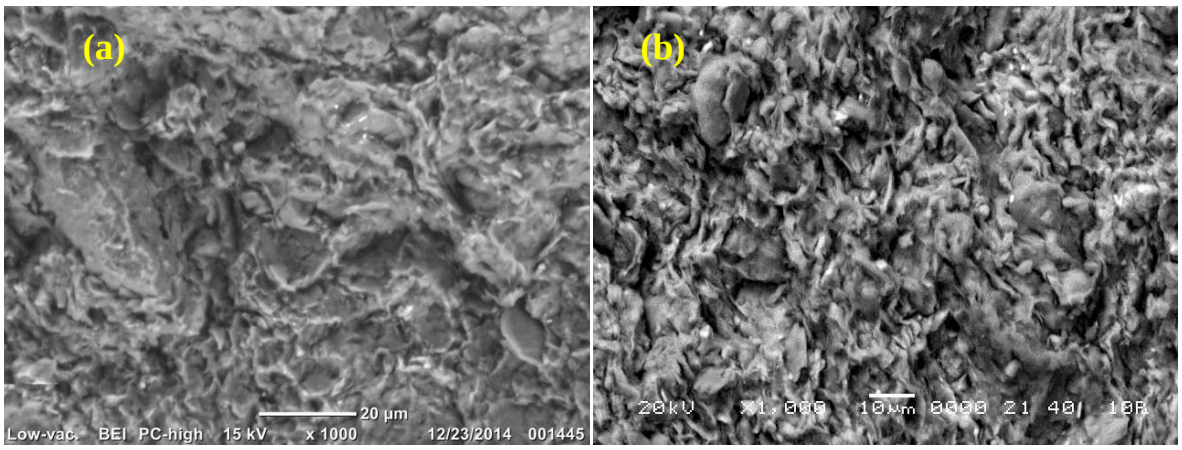

Figure 1 – a) SEM (JCM-6000) and b) SEM (JSM-5610LV) photographic images of the structure and morphological features of the studied fine colloidal dark green bentonite clays.

Differential thermal studies of bentonite clays of the Kyngrak-Keles deposit show (**Figure 2**) that the thermogram has characteristic signs of changes in their properties, where two endoeffects are observed. The first of them is recorded at a temperature of 100-180^{0}C, which is accompanied by a loss of mass and is associated with the release of free and adsorbed water. A small, weakly expressed endothermic effect in the range of 200-900^{0}C is associated with the removal of the main part of chemically bound (constitutional) water of various minerals: montmorillonite, hydromicas, hydrochlorite, kaolinite, micas, gypsum, which causes the absence of a clear endoeffect of their decomposition. In the same temperature ranges, the dissociation of various carbonates with the release of carbon dioxide mainly ends. In the range of 200-600^{0}C, the volatile part of organic impurities is released, and at 700^{0}C and above, sulfur dioxide from gypsum and oxidation of sulfides is released.

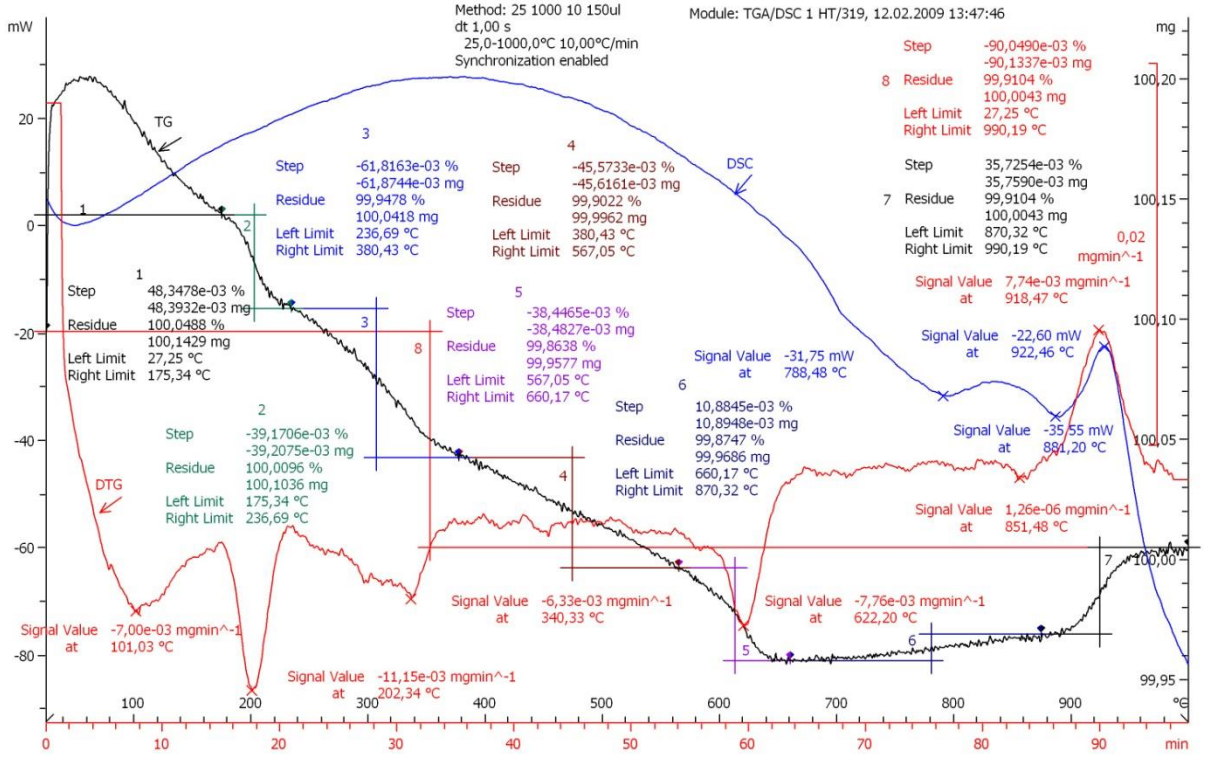

Figure 2 – Thermogram bentonite clays.

In this case, under the influence of reducing conditions, the reactions of interaction of minerals both among themselves and with organic impurities are significantly accelerated, with the release of a gaseous phase. Dehydration during firing is accompanied by a gradual destruction of their crystal lattices - kaolinite at 400-650^{0}C, montmorillonite and hydromica within 300-900^{0}C, and at 900-1050^{0}C, complete destruction of the crystal lattices of clay minerals and their amorphization with the release of residual constitutional water occurs, which increases their reactivity and the formation of a colossal number of micropores, which, along with the pores formed as a result of physical contact between the smallest elementary particles and their complexes, determine the overall porosity of the material in the period preceding its swelling.

Oxidation-reduction processes within the range of 300-1050^{0}C have a significant effect on phase transformations. The presence of organic impurities, iron oxides and constitutional water in the clay raw material creates favorable conditions for the development of reversible reactions with alternate oxidation and reduction of iron oxides, oxidation of carbon and hydrogen and reduction of their combustion products. At the same time, as the temperature increases, reduction reactions begin to predominate, accompanied by the accumulation of iron oxide, which does not disappear until the end of firing. The oxidation process of previously reduced iron begins only when the rate of water vapor release from dehydrating minerals decreases so much that it ceases to interfere with the diffusion of oxygen into the sample.

Research has shown that when firing expanded clay, all clay minerals and fluxes pass into the melt, forming pore walls where at 950-1050^{0}C a glass phase appears with the participation of ferrous oxide and other fluxes and local areas of weakly porous mass. Within the range of 1050-1200^{0}C, the overwhelming majority of expanded clay raw materials soften due to the formation of ever greater quantities of low-melting eutectics with the participation of fluxes, especially ferrous oxide and alkalis, and the assimilation of other finely dispersed components by the melt, and the mass passes into a pyroplastic state, characterized by a certain homogeneity of the melt and an optimal viscosity for swelling.

During the heat treatment, vaporous and gaseous products are released from a homogeneous mixture of minerals of the studied clays. When a homogeneous mixture of minerals of the studied clays is heated, chemical interaction occurs in the contact areas between them while still in solid phases, where, with an increase in temperature, as a result of further interaction of components, a liquid phase appears due to the most easily fusible eutectics and compounds, the amount of which continuously increases due to the appearance of new eutectics at higher temperatures and the interaction of the already formed liquid phase with crystalline components. With the appearance of a certain amount of liquid phase, as the temperature increases, the viscosity of the studied clay mass begins to decrease and plastically deform.

As studies have shown, during the firing process, under the influence of shrinkage deformations and rearrangement of structural elements, the number and size of pores, as well as the overall porosity of the material, change significantly, mainly determined by the mineralogical composition and degree of dispersion of the original clay raw material, while the finer the clay, the more low-temperature vapor-gas phase is released from the mineralogical components, the greater the microporosity of the material and vice versa.

As a result of thermal treatment of clays at a rate changing during the firing of expanded clay from 15-30 to 50-100 degrees/min, the reactions of decomposition, dissociation and interaction of the components of the mass with the release of gas-vapor products are somewhat shifted to the region of higher temperatures, providing resources of the gas-vapor phase for swelling of the material, which occurs in the range of 1050-1200^{0}C, to values characteristic of this clay raw material.

As the material is heated to 900-1000^{0}C, the total porosity with a changing nature of the pore size distribution continuously increases, then drops sharply during sintering. At the same time, it is important to note that the total porosity decreases mainly due to larger pores with an increasing number of tiny ones. The swelling interval is reduced by CaO, and at high content it causes rapid deformation and adhesion of the material, sharply reducing the viscosity of the liquid phase in a short temperature range, which significantly complicates burning.

Based on a comprehensive study of bentonite clays from the Kyngrak-Keles deposit, we have established that, based on their material (chemical and mineralogical) composition, bentonite clays belong to the montmorillonite-hydromica low-dispersion group of clay materials with fine-dispersed fractions of less than 10 μm.

Tire production waste is a powder produced during the mechanical processing of tyres. The powder was sieved through a sieve with a mesh size of 2 mm.

The results of tests of expanded clays from masses with the addition of tire production powder, shown in **Table 2** and **Figure 3**, **Figure 4**, indicate a positive effect of this additive on the bulking capacity of the clays under study.

When 0.5% of tire waste powder is added to the mass composition, expanded clay with a bulk density of less than 400 kg/m3 can be obtained already at a temperature of 1120^{0}C. Granules fired at 1160^{0}C have a bulk mass of 0.484 g/cm^3, which corresponds to the bulk mass of expanded clay about 280 kg/m^3 with a closed porosity of 77%.

Table 2
Physical and mechanical parameters of expanded clay on the basis of bentonite clay with the addition of tyre production waste

Burning temperature, ^{0}C	Swelling coefficient	Bulk mass, g/cm^3
0.5% of tyre production waste		
1080	1,8	0,858
1100	2,2	0,736
1120	2,7	0,584
1140	3,1	0,517
1160	3,2	0,484
1% of tyre production waste		
1080	2,3	0,699
1100	3,1	0,513
1120	3,3	0,483
1140	4,2	0,391
1160	4,7	0,353
1180	4,2	0,398
3% of tyre production waste		
1080	2,5	0,626
1100	2,6	0,605
1120	3,5	0,450
1140	3,6	0,430
1160	3,8	0,409
1180	3,6	0,436

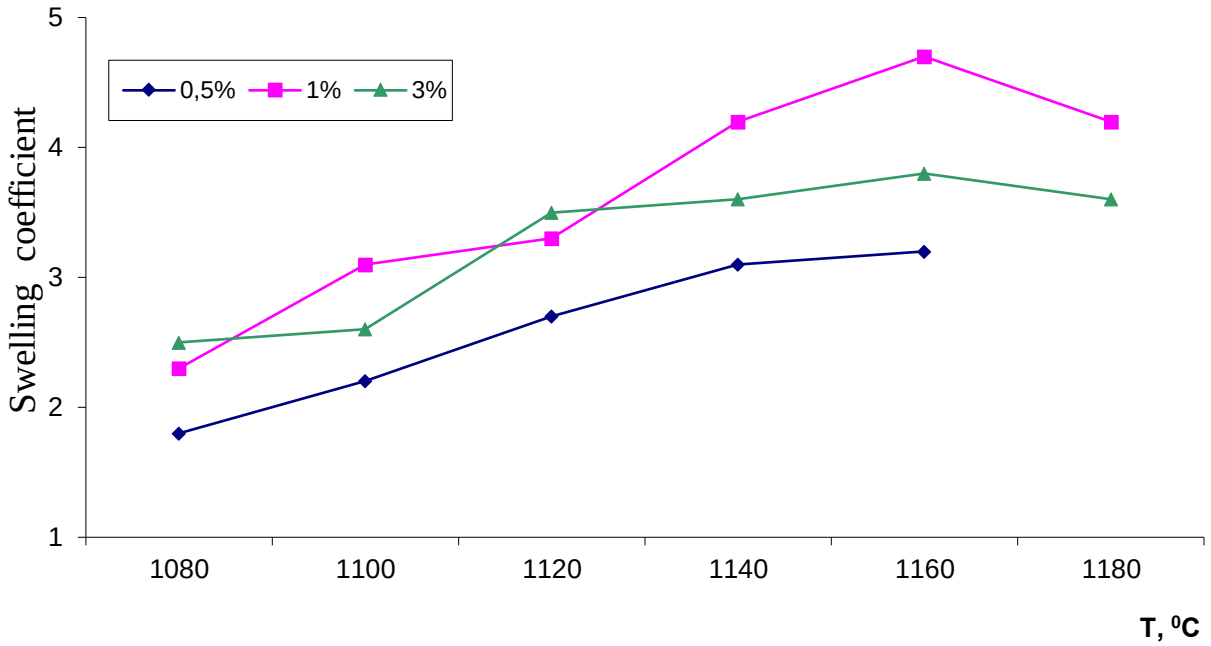

Figure 3 – Change in the swelling coefficient of the obtained expanded clay based on bentonite clays with the addition of tire production waste depending on the burning temperature.

From the mass with the addition of 1% of tire production waste powder, expanded clay can be obtained at a burning temperature of 1100^{0}C and higher. Closed porosity reaches more than 80%. The bulk mass of granules fired at 1160^{0}C = 0.350 g/cm^3, which corresponds to the bulk mass of expanded clay - 280 kg/m^3.

From the mass with the addition of 3% powder from tire production waste, expanded clay can be obtained at a burning temperature of 1080^{0}C. The bulk mass of granules fired at 1080^{0}C = 0.605 g/cm^3, which corresponds to the bulk mass of expanded clay - 400 kg/m^3.

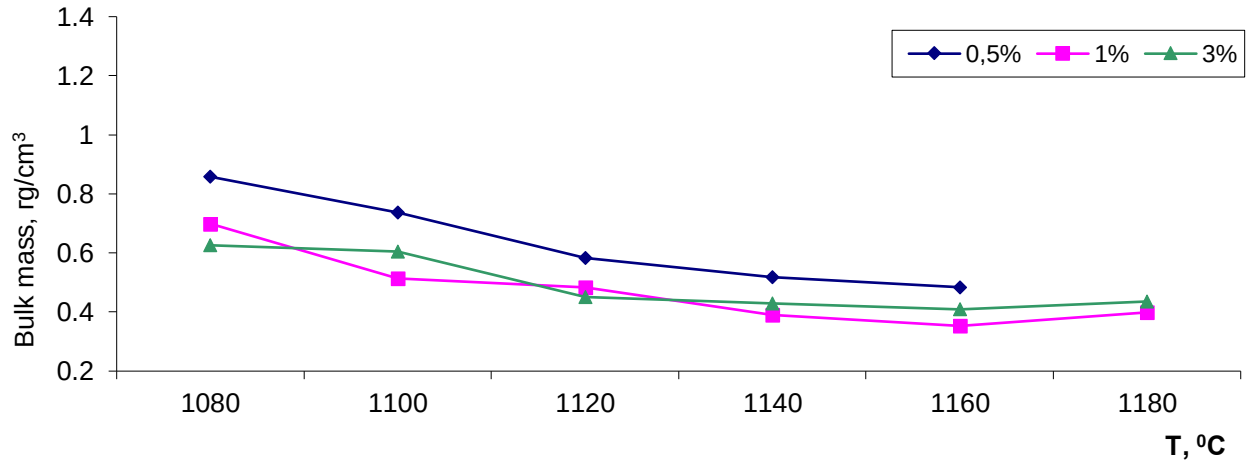

Figure 4 – Change in the bulk mass of the obtained expanded clay based on bentonite clays with the addition of tire production waste depending on the burning temperature.

5 CONCLUSIONS

1. It was established that for the studied clay the value of air linear shrinkage under conditions of slow natural drying is 10.8%, and under a strict artificial drying regime – 7.8%.

2. Fire shrinkage during firing of samples at a temperature of 950^0C is 5.5%.

3. It has been established that the addition of tire production waste to bentonite clays serves as a good swelling intensifier.

4. It has been confirmed that the optimal addition of tire production waste is 0.5-1% of the clay mass.

5. The optimum firing temperature for expanded clay was determined to be 1120^0C ± 20^0C.

6. It has been established that during heat treatment all clay minerals and fluxes pass into the melt, forming pore walls with the subsequent appearance of a glass phase, where the raw material already at the maximum temperature softens due to the formation of ever greater quantities of low-melting eutectics with the participation of fluxes and the assimilation of the melt of other finely dispersed components, after which the mass passes into a pyroplastic state, characterized by a certain homogeneity of the melt and an optimal viscosity for swelling and porization.

The presented results indicate that tire production waste is the best additive for the production of expanded clay from bentonite clays in lightweight concrete technology to improve the seismic resistance of brick buildings.

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RESEARCH ARTICLE

INVESTIGATION OF THE COMPOSITION OF ASH AND SLAG WASTE FROM THERMAL POWER PLANTS FOR USE IN BUILDING CERAMICS

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Abstract. *In the context of intensified housing construction and the transition to a "green" economy in the Republic of Kazakhstan, the demand for energy-efficient and environmentally friendly building materials is increasing. Against the backdrop of a shortage of high-quality clay raw materials, the use of ash and slag waste (ASW) from thermal power plants in the production of construction ceramics is becoming especially relevant. Chemical and phase analysis of ash and slag from Pavlodar TPP-3 and natural clay from the Pavlodar deposit has been made in the study. X-ray fluorescence analysis (XRF) and X-ray diffraction (XRD) methods have been applied using Bruker equipment. The data obtained have been interpreted according to current international standards. Ash and slag materials contain up to 61.19% SiO_2 and 18.61% Al_2O_3, as well as significant amounts of fluxing oxides (CaO, MgO, K_2O), which help reduce sintering temperature. The clay is characterized by high Al_2O_3 and Fe_2O_3 content, which makes it suitable for the production of red-fired ceramic products. X-ray fluorescence analysis confirmed the presence of such phases as quartz, mullite, and anorthite in the ash and slag, and kaolinite, illite, and feldspars in the clay. An integrated approach to combining ash and slag with clay allows to optimize the ceramic mass formulation, improving its plasticity and strength. The use of ash and slag waste in construction ceramics ensures technological efficiency and solves environmental problems by reducing industrial waste volumes, expanding the raw material base, increasing production profitability, and supporting sustainable development.*

Keywords: *Ash and slag, construction ceramics, phase composition, aluminosilicates, fluxing additives, heat resistance.*

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ҒЫЛЫМИ МАҚАЛА

ҚҰРЫЛЫС КЕРАМИКАСЫНДА ҚОЛДАНУҒА АРНАЛҒАН ЖЭО КҮЛ ҚОЖ ҚАЛДЫҚТАРЫНЫҢ ҚҰРАМЫН ЗЕРТТЕУ

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Аңдатпа. *Тұрғын үй құрылысының қарқындылығы және «жасыл» экономикаға көшу жағдайында Қазақстан Республикасында энергиялық тиімді және экологиялық таза құрылыс материалдарына қажеттілік артып келеді. Кондициялық саз шикізаты тапшы болғандықтан, құрылыс керамикасын өндіруде жылу электр орталығының (ЖЭО) күл-қож қалдықтарын (ККҚ) пайдалану ерекше өзекті болып отыр. Зерттеу барысында Павлодар ЖЭО-3 күл қождары мен Павлодар кен орнының табиғи сазына химиялық және фазалық талдау жүргізілді. Bruker жабдығын қолдана отырып, рентгендік флуоросцентті талдау (РФТ) және рентгендік дифракция (РД) әдістері қолданылды. Талдау деректері қолданыстағы халықаралық стандарттарға сәйкес түсіндірілді. Күл қож құрамында 61,19% дейін SiO_2 және 18,61% Al_2O_3, сондай-ақ күйдіру температурасының төмендеуіне ықпал ететін флюс оксидтерінің (CaO, MgO, K_2O) айтарлықтай мөлшері бар. Саз Al_2O_3 және Fe_2O_3 құрамының жоғарылауымен сипатталады, бұл оның қызыл жанғыш керамикалық бұйымдарды өндіруге жарамдылығын қамтамасыз етеді. Рентгендік флуоросцентті талдау күл қожындағы кварц, муллит және анортит, саздағы каолинит, иллит, дала шпаттары сияқты фазалардың болуын растады. Күл қождары мен сазды біріктірудің кешенді тәсілі керамикалық массаның рецептурасын оңтайландыруға, икемділік пен беріктікті жақсартуға. Құрылыс керамикасында ККҚ-ын қолдану технологиялық тиімділікті қамтамасыз етіп қана қоймай, сонымен қатар техногендік қалдықтардың көлемін азайтып, шикізат базасын кеңейту, өндіріс табыстылығын арттыру және тұрақты даму тұжырымдамасын қолдай отырып, экологиялық міндеттерді шешеді.*

Түйін сөздер: *Күл-қож, құрылыс керамикасы, фазалық құрам, алюминий силикаттары, флюс қоспалары, ыстыққа төзімділік*

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НАУЧНАЯ СТАТЬЯ

ИССЛЕДОВАНИЕ СОСТАВА ЗОЛОШЛАКОВЫХ ОТХОДОВ ТЭЦ ДЛЯ ПРИМЕНЕНИЯ В СТРОИТЕЛЬНОЙ КЕРАМИКЕ

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Аннотация. *В условиях интенсификации жилищного строительства и перехода к «зёленой» экономике в Республике Казахстан возрастает потребность в энергоэффективных и экологичных строительных материалах. На фоне дефицита кондиционного глинистого сырья особую актуальность приобретает использование золошлаковых отходов (ЗШО) ТЭЦ в производстве строительной керамики. В исследовании проведен химический и фазовый анализ золошлаков Павлодарской ТЭЦ-3 и природной глины Павлодарского месторождения. Применены методы рентгенофлуоросцентного анализа (РФА) и рентгеновской дифракции (РД) с использованием оборудования Bruker. Данные анализов интерпретированы в соответствии с действующими международными стандартами. Золошлаки содержат до 61,19 % SiO_2 и 18,61 % Al_2O_3, а также значительные количества флюсующих оксидов (CaO, MgO, K_2O), способствующих снижению температуры спекания. Глина характеризуется повышенным содержанием Al_2O_3 и Fe_2O_3, что обеспечивает ее пригодность для производства красножгущихся керамических изделий. Рентгенофлуоросцентный анализ подтвердил наличие таких фаз, как кварц, муллит и анортит в золошлаке, и каолинит, иллит, полевые шпаты в глине. Комплексный подход к сочетанию золошлаков и глины позволяет оптимизировать рецептуру керамической массы, улучшить пластичность и прочность. Применение золошлаковых отходов в строительной керамике обеспечивает не только технологическую эффективность, но и решает экологические задачи, снижая объемы техногенных отходов, расширяя сырьевую базу, повышая рентабельность производства и поддерживая концепцию устойчивого развития.*

Ключевые слова:. *Золошлаки, строительная керамика, фазовый состав, алюмосиликаты, флюсующие добавки, термостойкость.*

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CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

АЛҒЫС / ҚАРЖЫЛАНДЫРУ КӨЗІ

Зерттеу жеке қаржыландыру көздерін пайдалана отырып жүргізілді.

МҮДДЕЛЕР ҚАҚТЫҒЫСЫ

Авторлар мүдделер қақтығысы жоқ деп мәлімдейді.

БЛАГОДАРНОСТИ / ИСТОЧНИК ФИНАНСИРОВАНИЯ

Исследование проводилось с использованием частных источников финансирования.

КОНФЛИКТ ИНТЕРЕСОВ

Авторы заявляют, что конфликта интересов нет.

1 INTRODUCTION

In the context of active housing and infrastructure construction in the Republic of Kazakhstan, there is a steady growth in demand for ceramic building products. Such products are in demand due to their high strength, durability, thermal resistance, and compliance with modern energy efficiency requirements.

The development of building ceramics in the Republic of Kazakhstan holds one of the key positions in the state policy in the field of industrial and housing development. This direction is reflected, in particular, in the national project «Strong Region – Driver of Country's Development» for 2021-2025, the main goal of which is to improve the quality and affordability of housing.

Additionally, within the framework of implementing the Concept for the transition to a «Green» economy, emphasis has been placed on expanding the use of environmentally friendly and energy-efficient materials, including ceramic products. The regulatory framework also supports these goals: current building codes and technical regulations contain requirements aimed at ensuring the quality, safety, and environmental sustainability of construction products on the domestic market.

Despite the presence of significant reserves of natural clays, certain regions of Kazakhstan are experiencing a shortage of high-quality clay raw materials, which affects the sustainability and volume of ceramic product manufacturing. According to the Ministry of Industry and Construction of the Republic of Kazakhstan, in 2021, domestic enterprises provided only 44% of the internal demand for ceramic bricks, highlighting the need to seek alternative raw material solutions.

One of the potential solutions may be the use of ash and slag waste (ASW) from thermal power plants (TPPs), which allows for the simultaneous resolution of resource conservation and environmental safety issues. According to statistics, approximately 1.9 million tons of ash and slag are processed annually in Kazakhstan, accounting for less than 8% of the total amount generated. The Committee for Environmental Regulation and Control of the Ministry of Ecology and Natural Resources of the Republic of Kazakhstan estimates that over 17 million tons of ash are sent to ash dumps each year. Projections indicate that without large-scale utilization, the total volume of accumulated ash and slag could reach 1 billion tons by 2030.

Against this backdrop, the scientific and practical importance of developing technologies for processing ash and slag as a component of forming masses for construction ceramics is increasing. Among the fundamental works dedicated to this area, it is worth noting the monograph by S. Zh. Saibulatov, S. T. Suleimenov, and A. V. Ralko titled «Ash-Ceramic Wall Materials» **(Saibulatov et.al., 1982)**, which provides a detailed examination of the mechanisms of mineral formation, phase transformations, and strength characteristics of products based on ash and clay.

2 LITERATURE REVIEW

A number of works by Russian and Kazakh researchers confirm the applicability of ash and slag waste (ASW) as a plasticizing and fluxing additive that improves the technological properties of ceramic masses **(Nemushchenko et.al., 2024; Malchik et. al., 2016; Vatin et.al., 2016).**

Using the example of ash and slag from the Tolyiatti Thermal Power Plant, their ability to correct the plasticity and thermal resistance of ceramic mixtures was established **(Safronov et.al., 2021)**. Other studies **(Abdrakhimov, 2019; Gostev & Karagulov, 2020; Abdullaeva & Takibaeva., 2024; Aleksandrova & Korchevenkov, 2017)** demonstrated the possibility of producing solid M150

bricks with the addition of up to 25% ASW, as well as a reduction in energy costs for drying and firing processes.

Industrial examples have also been implemented in Kazakhstan: at Pavlodar brick factory No. 3, the addition of 12-15% ash and slag from TPP-1 helped eliminate shrinkage and cracking of the clay mass, increase strength, and improve the geometry of products **(Lazareva & Kulikova, 2016)**. Ash and slag from the Ekibastuz GRES-1, containing up to 25.7% Al_2O_3 and SiO_2 were successfully used, demonstrating strength up to 17 MPa when fired at 1000-1050º C **(Akhmedyanov et.al., 2015)**.

In addition, the formulations developed in the Pavlodar region with the participation of ASW confirm the industrial applicability of this approach **(Aryngazin et.al., 2022; Shaimerdenov & Shukurov, 2024; Vyshar et.al., 2023; Aldungarova et.al., 2021)**.

Additional research once again confirms the expediency of using ash and slag waste from thermal power plants in the production of ceramics. A comprehensive assessment of the ASW composition revealed the presence of reactive aluminosilicate microspheres, which improved water retention capacity and enhanced the physical-mechanical properties of mineral-based materials **(Kosivtsov et al., 2021)**. A modern approach to incorporating ash and slag waste into ceramic technology was demonstrated in a study focusing on three-component mixtures composed of aluminosilicate loams, ASW from thermal power plants, and fluxing additives such as cullet and silica gel. These additives enhanced mineral formation during firing, reduced the required heat treatment temperature, and increasing mechanical strength compared to binary compositions (loam + ASW) **(Gur'eva & Doroshin, 2024).**

3 MATERIALS AND METHODS

X-ray fluorescence (XRF) analysis was conducted using a Bruker spectrometer S2 Puma, and identification and quantification of crystalline phases using X-ray diffraction (XRD) on a Bruker diffractometer D6 PHASER. Both instruments are calibrated according to the manufacturer's standards and certified references, ensuring metrological traceability and high data reproducibility.

In the case of XRF, the pressed tablet or fused bead method was used, depending on the nature of the sample. For finely dispersed samples, pressing with an inert binder under a pressure of 20 t/cm² was applied (ASTM C114-23, ASTM E1621-13). Calibration was performed using CRM/ERM standards with expected concentration ranges. Spectrum recording was performed at 50 kV – 50 mA (Rh tube), collimator – 0.5 mm; calculation – by fundamental regression with peak overlap correction and verification using internal control samples (RSD < 2 %).

Samples for XRD were ground to < 63 μm in a planetary mill, ensuring random packing. Bragg-Brentano geometry was used with Cu Kα tube (λ =1.5406 Å), 40 kV – 40 Ma, slit – 0.6 mm, graphite monochromator. Scanning parameters: 5º – 70º 2θ, step 0.02, 1 s/step. Qualitative phase analysis was carried out according to the ICDD database PDF 4+ (2025).

Quality control included repeated measurements every 10 samples, laboratory blanks, and daily adjustments. This allowed keeping RSD below 0.5% for major elements (XRF) and < 1 % for peak intensities (XRD).

Figure 1 shows the ash and slag waste used at the Pavlodar TPP-3 and clay from the Pavlodar deposit.

Figure 1 – The studied ash and slag waste and clay [author's material].

4 RESULTS AND DISCUSSION

This study aims to assess the suitability of ash and slag waste from the Pavlodar region thermal power plant for the production of building ceramics. The efficiency of ash and slag use is determined by their compliance with the physical and chemical requirements for clay raw materials: dispersion, phase composition, oxide, and impurity content.

Ash and slag from thermal power plants are a finely dispersed gray material consisting of microspheres and angular particles. According to the data of the reclamation project for the ash dump of thermal power plant 2, up to 88% of the particles are 0.25-0.01 mm in size, which provides favourable conditions for the formation of a dense ceramic structure.

The composition of Ekibastuz ash and slag is represented by aluminosilicates, including mullite, quartz, hematite, and magnetite. Chemically, the oxides SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, and TiO_2 predominate.

The established characteristics confirm the potential applicability of ash and slag from TPP-3 as a functional component in the composition of clay raw materials for building ceramics.

X-ray fluorescence (XRF) analysis allowed determining the mass fraction of the main oxides in the studied samples: ash and slag from Pavlodar TPP-3 (Sample 1) and natural clay from the Pavlodar deposit (Sample 2).

Ash and slag are dominated by SiO_2 (61.19%) and Al_2O_3 (18.61%), which determines their aluminosilicate nature. A significant content of Fe_2O_3 (14.49%), as well as fluxing oxides K_2O, CaO, MgO, in total exceeds 10%, which makes it an effective component for lowering the sintering temperature.

The clay is characterized by a higher content of Al_2O_3 (28.39%) and Fe_2O_3 (26.88%), with a comparatively moderate proportion of SiO_2 (51.08%), which contributes to its tendency for intense coloration and the formation of a dense ceramic body at firing temperatures of 1100–1200 ºC. The comparative oxide composition of ash and clay is presented in **Table 1**.

Table 1
Comparative oxide composition of the studied samples [author's material]

Name of the raw material component	Oxide composition, mass %								
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	TiO_2	K_2O	SO_3
Clay	51.08	28.39	14.32	2.9	0.9	0.02	1.32	0.48	0.19

ASW of TPP-3	6 1.19	18.61	7.64	3.86	3.46	0.09	0.95	3.36	0.4

The chemical characteristics of the ash-slag waste allow it to be considered both as a fluxing and structural additive. The high content of fluxing components (K_2O, CaO, MgO) ensures a reduction in the initial sintering temperature, while Al_2O_3 and SiO_2 provide structural stability under thermal exposure. The presence of Fe_2O_3 contributes to the formation of an intense coloration.

The clay belongs to high-alumina, red-firing masses. The high concentration of Al_2O_3 ensures thermal resistance and shape stability during firing. The increased Fe_2O_3 content determines the characteristic dark-red coloration of the products. The combined data indicate the feasibility of blending ash-slag waste with clay to optimize the recipe of the ceramic mass.

X-ray phase analysis, performed in the 2θ range from 5º to 70º, made it possible to determine the mineral composition of the studied samples – ash and slag as shown in **Figure 2** and clay as shown in **Figure 3.**

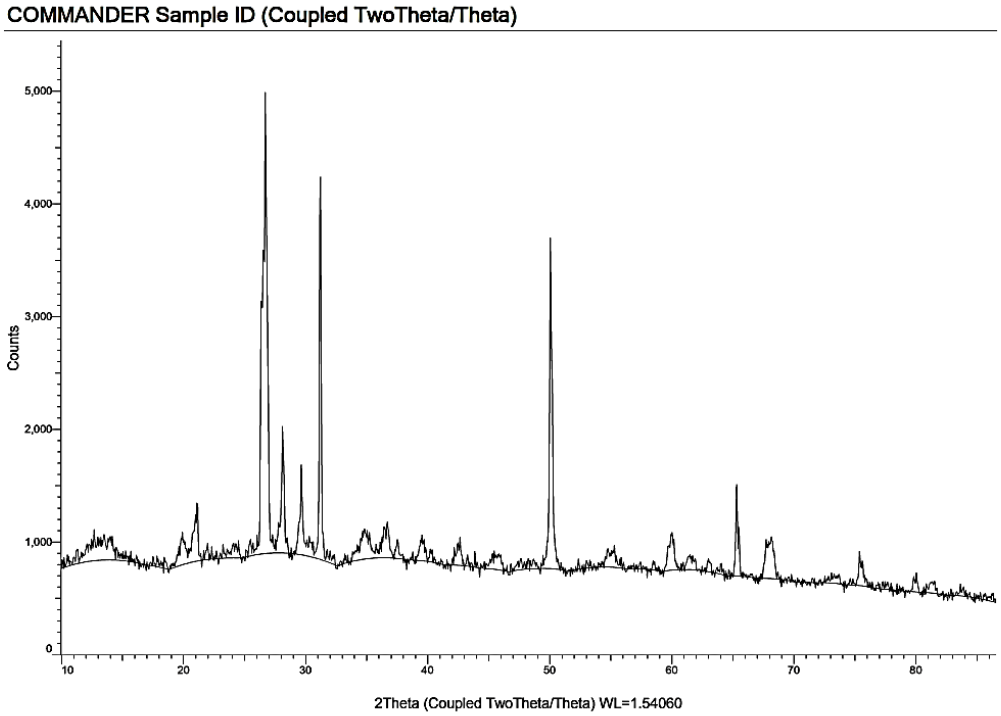

Figure 2 – Diffractogram of ash and slag from TPP-3 in Pavlodar region [author's material].

The ash-slag sample is characterized by an intense peak around 26.6º 2θ, which corresponds to the main reflection of quartz (SiO_2). Additionally, reflections corresponding to mullite ($Al_6Si_2O_{13}$) and anorthite ($CaAl_2Si_2O_8$) were identified. The presence of a broad background in the range of 15–35º indicates the existence of an amorphous glassy phase. Secondary peaks may be associated with hematite (Fe_2O_3) and rutile (TiO_2), which supports the chemical analysis data regarding Fe and Ti content.

The clay sample contains phase components typical of clay raw materials: kaolinite (peaks at ~12.3º, ~24.9º, ~38.5º), illite/muscovite (peaks at ~8–10º, ~17–20º, ~26º), as well as feldspars (orthoclase, microcline, albite) in the 28–31º 2θ range. The presence of hematite is confirmed by peaks in the 33–35º and ~54º ranges. An intense quartz peak (~26.6º) also dominates, indicating a

significant content. The amorphous component, expressed by a broad background, is characteristic of fine-grained phases and poorly ordered silicates.

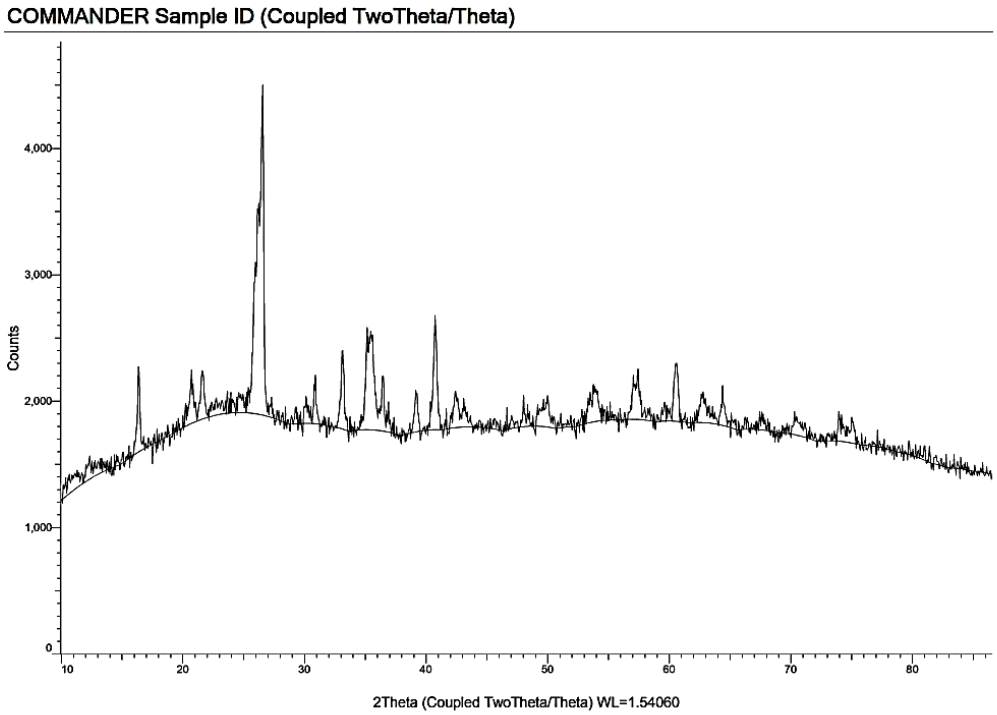

Figure 3 – Diffractogram of clay from the Pavlodar deposit

5 CONCLUSIONS

Based on the research results, the following conclusions can be drawn:

1. The chemical and phase analyses have confirmed that ASW from thermal power plants can be effectively used as a functional additive to clay raw materials for the production of building ceramics.

2. The presence of fluxing oxides (K_2O, CaO, MgO) and amorphous glassy phases in the ASW facilitates low-temperature sintering, while aluminosilicates (SiO_2, Al_2O_3) provide structural integrity and thermal resistance of the ceramic body.

3. The studied ash and slag from the Pavlodar TPP-3 are compatible with the high-alumina red-firing clays from the Pavlodar deposit, supporting the formation of dense, thermally stable ceramic materials.

4. The use of ASW in ceramic formulations reduces energy consumption during firing and contributes to cost saving in ceramic production.

5. Incorporating ASW into building ceramics promotes environmental sustainability by reducing the volume of industrial waste and mitigating its environmental impact, while simultaneously expanding the raw material base.

Further research should be aimed at optimizing the composition of ceramic products by selecting an effective ratios of ash and slag waste.

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RESEARCH ARTICLE

OPTIMIZATION OF EXPANDED CLAY CONCRETE MIXTURE FOR MODULAR STRUCTURES WITH CONSIDERATION OF SUSTAINABILITY

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Abstract. *The purpose of this study is to experimentally substantiate the effect of the concrete mixing methods on the physical and mechanical properties of expanded clay concrete used in modular construction. In the framework of research two technological approaches of mixing are compared: traditional (according to GOST) and alternative method of "suspension concrete". The study was conducted on identical compositions of lightweight concrete with expanded clay aggregates with fractions of 0-10 mm at a constant dosage of cement, sand, water and chemical admixtures. Control samples were produced for each mixing method and compressive strength tests were conducted at the ages of 1, 3, 7 and 28 days to determine the average density of the samples. The results show that changing the order of introducing the components has a significant impact on material structure formation. The use of the suspension mixing method, in which a cement-water suspension is formed before the introduction of aggregates, provides an increase in the strength of expanded clay concrete by up to 19% on day 28 compared to traditional technology. In addition, there was an improvement in the uniformity and surface quality of samples. At the same time, workability and the density of the concrete mixture remained at the same level. Therefore, suspension mixing can be considered an effective way to strengthen the structure of expanded clay without changing its composition, which is particularly important in industrial production of precast products. The obtained data are of practical significance and can be used to improve production technologies for lightweight concrete with enhanced performance properties.*

Keywords: *expanded clay concrete, lightweight concrete, mixing method, suspension concrete, compressive strength, density, modular construction.*

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ҒЫЛЫМИ МАҚАЛА

ТҰРАҚТЫЛЫҚТЫ ЕСКЕРЕ ОТЫРЫП, МОДУЛЬДІК КОНСТРУКЦИЯЛАР ҮШІН КЕҢЕЙТІЛГЕН САЗДЫ БЕТОННЫҢ ҚҰРАМЫН ОҢТАЙЛАНДЫРУ

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Аңдатпа. *Бұл зерттеудің мақсаты модульдік Құрылыста қолданылатын кеңейтілген сазды бетонның физика-механикалық сипаттамаларына бетон қоспасын араластыру әдісінің әсерін эксперименттік негіздеу болып табылады. Зерттеу аясында араластырудың екі технологиялық тәсілін салыстыру жүргізілді: дәстүрлі (ГОСТ бойынша) және балама "суспензиялық бетон"әдісі. Зерттеу цемент, құм, су және химиялық қоспалардың тұрақты дозасында 0-10 мм фракциялық кеңейтілген сазды агрегаты бар жеңіл бетонның бірдей құрамдарында жүргізілді. Араластырудың әр әдісі үшін бақылау үлгілері жасалды және 1, 3, 7 және 28 тәулік жасында қысу беріктігі сыналды, сонымен қатар үлгілердің орташа тығыздығы анықталды. Нәтижелер бетон қоспасының компоненттерін енгізу тәртібінің өзгеруі материалдың құрылымын қалыптастыруға айтарлықтай әсер ететіндігін көрсетті. Суспензияны араластыру әдісін қолдану, онда цемент-су суспензиясы агрегаттар енгізілгенге дейін қалыптасады, дәстүрлі технологиямен салыстырғанда кеңейтілген сазды бетонның беріктігінің 28 тәулікке 19% - ға дейін өсуін қамтамасыз етті. Сонымен қатар, үлгілердің біртектілігі мен бетінің сапасы жақсарды. Бетон қоспасының жұмыс қабілеттілігі мен тығыздығы бірдей деңгейде қалды. Осылайша, суспензияны араластыруды композицияны өзгертпестен кеңейтілген сазды бетон құрылымын күшейтудің тиімді әдісі ретінде қарастыруға болады, бұл әсіресе Құрама бұйымдардың өнеркәсіптік өндірісі жағдайында маңызды. Алынған мәліметтер қолданбалы мәнге ие және өнімділігі жоғары жеңіл бетон жасау технологияларын жетілдіру үшін пайдаланылуы мүмкін.*

Түйін сөздер: *керамзитбетон, жеңіл бетон, араластыру әдісі, суспензиялық бетон, қысуға беріктік, тығыздық, модульдік құрылыс.*

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НАУЧНАЯ СТАТЬЯ

ОПТИМИЗАЦИЯ СОСТАВА КЕРАМЗИТОБЕТОНА ДЛЯ МОДУЛЬНЫХ КОНСТРУКЦИЙ С УЧЕТОМ УСТОЙЧИВОСТИ

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Аннотация. *Целью настоящего исследования является экспериментальное обоснование влияния способа перемешивания бетонной смеси на физико-механические характеристики керамзитобетона, применяемого в модульном строительстве. В рамках исследования выполнено сравнение двух технологических подходов к перемешиванию: традиционного (по ГОСТ) и альтернативного метода «суспензионного бетона». Исследование проводилось на одинаковых составах легкого бетона с керамзитовым заполнителем фракции 0–10 мм при постоянной дозировке цемента, песка, воды и химических добавок. Для каждого способа перемешивания были изготовлены контрольные образцы и проведены испытания прочности на сжатие в возрасте 1, 3, 7 и 28 суток, а также определена средняя плотность образцов. Полученные результаты показали, что изменение порядка введения компонентов бетонной смеси оказывает существенное влияние на формирование структуры материала. Применение метода суспензионного перемешивания, при котором цементно-водная суспензия формируется до ввода заполнителей, обеспечило прирост прочности керамзитобетона до 19% на 28 сутки по сравнению с традиционной технологией. Кроме того, было отмечено улучшение однородности и качества поверхности образцов. Удобоукладываемость и плотность бетонной смеси при этом оставались на одинаковом уровне. Таким образом, суспензионное перемешивание может рассматриваться как эффективный способ интенсификации структуры керамзитобетона без изменения состава, что особенно актуально в условиях промышленного производства сборных изделий. Полученные данные имеют прикладное значение и могут быть использованы для совершенствования технологий изготовления легких бетонов с повышенными эксплуатационными характеристиками.*

Ключевые слова: *керамзитобетон, легкий бетон, способ перемешивания, суспензионный бетон, прочность на сжатие, плотность, модульное строительство.*

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CONFLICT OF INTEREST

The authors state that there is no conflict of interest

АЛҒЫС / ҚАРЖЫЛАНДЫРУ КӨЗІ

Зерттеу жеке қаржыландыру көздерін пайдалана отырып жүргізілді.

МҮДДЕЛЕР ҚАҚТЫҒЫСЫ

Авторлар мүдделер қақтығысы жоқ екенін растайды.

БЛАГОДАРНОСТИ/ИСТОЧНИК ФИНАНСИРОВАНИЯ

Исследование проводилось с использованием частных источников финансирования.

КОНФЛИКТ ИНТЕРЕСОВ

Авторы подтверждают, что конфликта интересов нет.

1 INTRODUCTION

Modern construction is moving towards industrialized and modular production methods, which requires the use of lightweight, durable, and technologically advanced concrete mixtures that ensure structural reliability and sustainability. Expanded clay concrete, a type of lightweight concrete made with porous aggregate, has become increasingly popular due to its low density, satisfactory strength, and enhanced thermal and acoustic insulation properties.

One of the most promising areas for the use of this material is in modular construction. Here, reducing the dead weight of the structures directly affects their transportability, assembly, and load on the foundation.

However, one of the main challenges limiting the widespread adoption of expanded clay concrete is its heterogeneous structure and reduced strength. This is particularly true in the contact zones between the expanded clay grains and the cement matrix. This is because of the high porosity of the clay aggregate and the weak adhesion at the interface.

In the context of implementing the Sustainable Development Goals (SDG 9 - Industrialization, SDG 11 - Sustainable Cities, and SDG 12 - Responsible Consumption and Production), it is an urgent task to optimize not only the composition but also the technical parameters of concrete mixture preparation. One of the most effective ways to conserve resources and enhance performance is to enhance mixing techniques. In this study, the "suspension concrete" method is explored, in which a cement-water paste is formed prior to the addition of aggregates. This approach is believed to contribute to a more homogeneous distribution of the binding agent, reduce delamination, improve uniformity, and increase strength due to enhanced coating of clay granules.

The current study aims to optimize the composition of expanded clay concrete for use in modular structures, considering the requirements for strength, manufacturing processability, and sustainability. Additionally, it aims to assess the impact of suspension mixing techniques on the physical, mechanical, and structural properties of the material.

2 LITERATURE REVIEW

Expanded clay concrete is a lightweight concrete based on a porous aggregate (expanded clay gravel or sand). It is widely used in construction due to its combination of sufficient strength and reduced density. This reduces the mass of structures and improves their thermal protection properties (**Rashad 2018; Zega and Di Maio, 2011**). However, the porosity of the lightweight aggregate and the structural features of expanded clay concrete can lead to the fact that the strength characteristics of such concrete are lower than those of heavy concrete of the same cement concentration (**Litsomboon et al., 2008**). An important task is to increase the strength and uniformity of expanded clay concrete without significantly increasing its density. It is known that technological factors in the preparation of a concrete mixture – in particular, the mode and sequence of mixing of the components – can significantly affect the formation of the structure of cement stone and the contact zone with the aggregate, and therefore the strength and durability of concrete (**Ozolins et al., 2021; Amran et al., 2015**).

Currently, expanded clay concrete is actively used in industrial housing construction, including the production of volumetric modular blocks for residential and commercial buildings. In particular, expanded clay concrete is used at the ModeX Astana enterprise as the main structural material in the manufacture of factory-ready modules (**Teshev et al., 2024**). This approach allows not only to reduce

construction time, but also to ensure high energy efficiency and durability with minimal weight of elements.

Numerous studies indicate that the properties of expanded clay concrete depend not only on the composition, but also on the technological parameters of preparation. The standard technology for the preparation of concrete mixtures, regulated by regulatory documents (for example, GOST 27006-2019 and GOST 7473-2010), usually involves the sequential introduction of components: first dry aggregates, then cement, then water with additives, with intermediate mixing. The mixing technology of the components has a significant impact on the properties of expanded clay concrete, especially when using lightweight aggregates such as LECA. The high porosity of expanded clay requires precise selection of the mixing mode and the order of the components to ensure the uniformity of the mixture and the strength of the material. Scientists (**Li et al., 2017**) proposed a method for designing the LWASCC composition that takes into account the thickness of the cement shell around the grains and the packing density. They emphasized that uniform distribution of the solution is possible only with strict control of the water-cement ratio and the mixing stage. Исследователи (**Kaffetzakis & Papanicolaou, 2016**) pointed out the need to pre-create a cement paste before adding aggregates to increase the stability of the composition and prevent delamination. Their colleagues take a similar position (**Vakhshouri & Nejadi, 2016**), focusing on step-by-step and "soft" mixing. Researchers (**Bogas & Gomes, 2013**) associate the nature of the fracture and the strength properties of light concrete with the quality of the contact zone between expanded clay and cement stone, which directly depends on the mixing technology. In their works (**Issa & Al-ASADI, 2022**), they also note that the saturation of the aggregate and the order of component insertion significantly affect the mechanical properties of LECA concrete. Scientists (**Dabbaghi et al.. 2022**) have confirmed that pre-dispersion of cement in water makes it possible to increase the strength, uniformity and fire resistance of concrete. The study (**Uysal et al., 2024**) showed that the effectiveness of using expanded clay directly depends on the mixing sequence and the quality of coating the grains with cement paste..

One of the promising methods is the so-called "suspension concrete", in the preparation of which a cement-water suspension (cement "paste" with chemical admixtures) is first created, and only then aggregates are injected. It is assumed that this mixing method can provide a more uniform coating of expanded clay grains with cement mortar and filling of pores, which should have a beneficial effect on the structure of concrete (**Demissew, 2022; Xu & Garrecht, 2024**). Studies (**Ahmad & Chen, 2019**), as well as (**Ahmad et al., 2019**) show that lightweight concretes based on expanded clay aggregate are characterized by a sensitive contact zone structure, especially with a high water-cement ratio. To increase uniformity and strength, such formulations require optimization of cooking technology. In particular, researchers (**Bogas et al., 2012**) indicated that the preliminary formation of the cement suspension before the injection of aggregates contributes to the uniform distribution of the binder and reduces the effect of water extraction with a porous aggregate. In their work (**Kroviakov et al., 2019**) note that the mixing sequence has a significant impact on the formation of quality criteria for expanded clay concrete, including strength, uniformity and resistance to segregation.

In this article, the effect of two different mixing methods, traditional (according to GOST), is experimentally investigated and suspension – for the strength and density characteristics of expanded clay concrete. The aim of the study is to determine how a change in the sequence of component introduction and mixing mode affects the density of the mixture, workability, strength gain dynamics and the quality of the structure of lightweight concrete on expanded clay aggregate with fraction 0-10 mm.

3 MATERIALS AND METHODS

The tests were carried out on an expanded clay concrete mixture with the same composition prepared in two different ways: according to the traditional method (GOST 27006-2019) and using the "suspended concrete" method. The cement used was Portland cement CEM I - 42.5 H produced by Central Asian Cement JSC (Kazakhstan), conforming with GOST 31108-2020 "Cements. General Technical Conditions". Construction sand used as a fine aggregate, with a grain modulus of M_k=3.2, and bulk density of 1637 kg/m³ (from the village of Kyzyljar, Akmolinsk region). The granulometric composition of the sand confirmed to GOST 8735 - 88 "Sand for Construction Works. Test Methods" as shown in **Table 1**.

Table 1
Granulometric composition of sand (author's materials).

No	The size of the sieve cell, mm	Full residual, %
1	2.5	25.1
2	1.25	43.1
3	0.63	72.9
4	0.315	88.9
5	0.16	98.7
6	<0.16	100

Expanded clay gravel with a particle size of 0-10 mm was used as a lightweight porous aggregate (**Figure 1**), provided by Stroitel LLP in Taldykorgan. The bulk density of the material is 585 kg/m³, which corresponds to GOST 9757-90 and GOST 9786-86 standards.

Figure 1 – Expanded clay fractions of 0-10 mm (author's materials).

The chemical admixture MC PowerFlow 7951H, produced by MC-Bauchemie in Germany, was used to improve the workability and manufacturability of the concrete mixture. This admixture corresponds with the European standard EN 934-2 and the ISO 14001:2016 standard for environmental management systems. The dosage of the admixture was 1% of the weight of cement, which is approximately 4.6 kilograms per cubic meter of concrete.

Drinking water was used to mixing the concrete, and it meets the requirements of the ST RK 1015-2000 standard for "Water. Gravimetric method for determining sulfate content in natural

wastewater", as well as the GOST 23732-2011 standard for "Water for concrete and mortar. Technical specifications."

The compositions of the concrete mixtures are presented in **Table 2**. The first mixing, with composition No. 1, was prepared according to the traditional method in accordance with GOST 27006-2019. First, dry aggregates (sand and expanded clay), measured in advance, were loaded into a mixer and mixed for 30 seconds. Then, cement was added, and the dry mixture was mixed again (for 30-60 seconds). After that, a measured amount of water was added, pre-mixed with a liquid admixture. The mixture was stirred until it became smooth (for another 1-2 minutes).

The second mixing, with composition No. 2, was prepared using the "suspended concrete" method. All the calculated water, along with the chemical admixture dissolved in it, was poured into the mixer first. Cement was then added immediately, while stirring, to create a homogeneous cement-water mixture within 1 minute. Sand and expanded clay, pre-weighed, were then added to the cement paste, and the mixture was further mixed for another 1-2 minutes to achieve the desired consistency. In both cases, the total mixing time was three minutes.

Table 2
Compositions of concrete mixtures (author's materials).

No of specimen	Cement, kg	Coarse sand, kg	Expanded clay fractions 0–10mm, kg	PCE, kg	Water, kg
1	0.460	1.030	0.351	0.046	0.220
2	0.460	1.030	0.351	0.046	0.220

The readiness of the concrete mixture was assessed based on its workability and density. We used the slump test method to check the workability of the mixture according to GOST 10181-2014. The density of the freshly mixed concrete was measured by filling a known volume measuring cone and weighing it, also according to GOST. Control samples were taken from each batch of the prepared mixture for strength testing. Metal cube molds with a size of 100×100×100 cm were used, and a total of eight samples were prepared for each composition. Two samples were tested at each age: 1, 3, 7, and 28 days after mixing. After casting, all samples were subjected to the same holding regimen: initially, they were treated with heat and moisture in a chamber according to the plant's technological process.

Compressive strength was determined in accordance with GOST 10180-2012 using a hydraulic press and by breaking cubes with flat faces. The quality and uniformity of the concrete were controlled in accordance with GOST 18105-2018, and the classification of the concrete by density and strength was assessed in accordance with the requirements of GOST 25820-2014 for lightweight concretes.

4 RESULTS AND DISCUSSION

The workability of the concrete mixture for both compositions was between 25 and 27 centimeters, which indicates that the mixtures have equally high workability and are close to self-flowing, confirming the technological compatibility of the method with current production lines.

As shown in **Figure 2**, the density of the concrete mixtures did not differ significantly, with values of 1831 kg/m^3 and 1835 kg/m^3, respectively. Additionally, the density of the concrete has significantly improved with the new mixing method, with the average density of suspended concrete

samples being 10 - 30 kg/m^3 higher than that of concrete produced according to GOST standards. For example, after 28 days, the density of specimens from composition No. 2 was 1753 kg/m^3, while that of composition No. 1 was 1723 kg/m^3. An increase in the density indicates a more compact structure and lower overall porosity in the material produced using the suspension mixing technique.

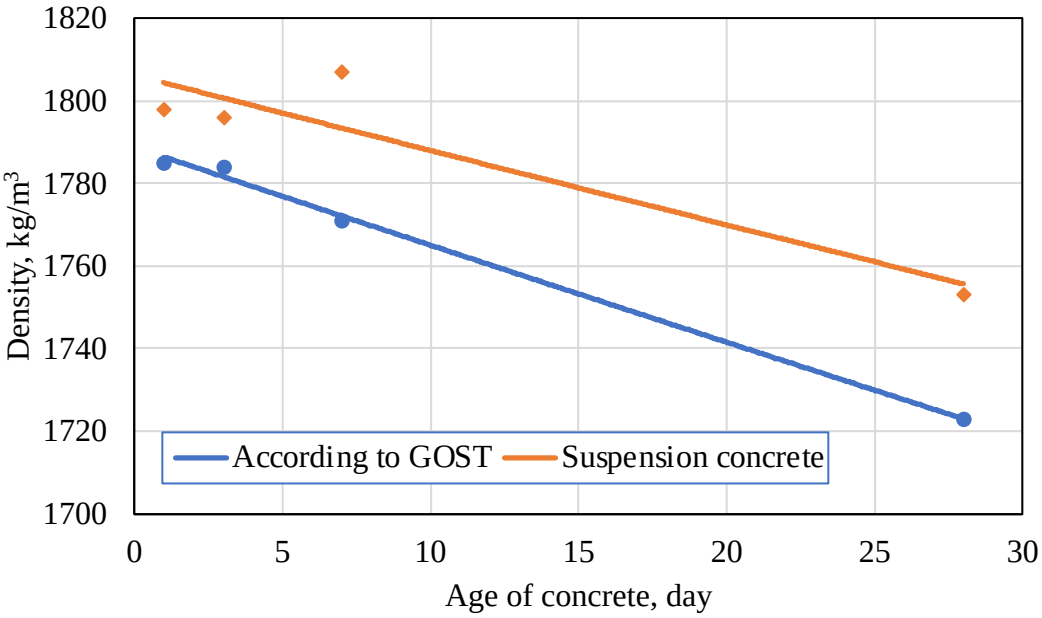

Figure 2 – Dependence of density on age of concrete (author's materials).

The comparative dynamics of strength gain for the two compositions are shown in **Figure 3**. On the first day, the difference between the two was minimal, with the strength of concrete made using the traditional method being 20.1 MPa and that of the suspension-based concrete being 19.45 MPa. However, by the third day, the strength of the suspension concrete began to steadily outpace the traditional concrete, reaching 22.2 MPa by the seventh day. By day 28, this difference had significantly increased, with the suspension concrete showing a strength of 27.8 MPa compared to the 23.3 MPa of the control sample, an increase of almost 19%.

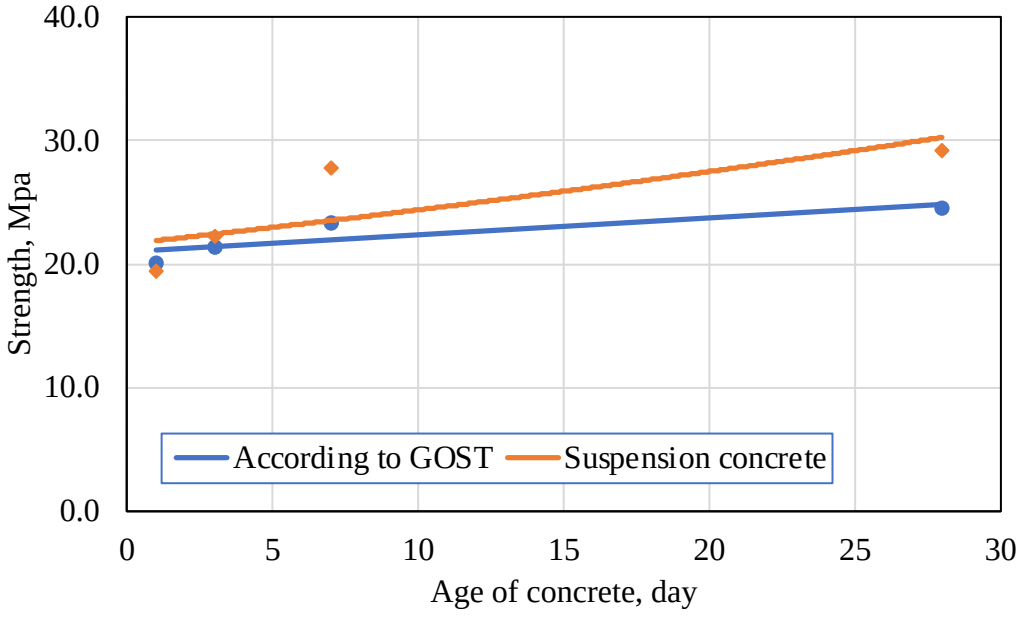

Figure 3 – Dependence of compressive strength on the age of concrete (author's materials).

The maximum effect was seen on day 28, where the strength of suspension concrete reached 29.2 MPa, compared to 24.5 MPa for the control mixture. This represents an increase in strength of 19% compared to the traditional method, indicating an increase in concrete grade and more efficient use of cement in the same composition.

In addition to the quantitative indicators of strength and density, a difference in the quality of the hardened concrete structure was recorded. A visual inspection of the samples revealed that the surface of the expanded clay concrete produced by the suspension method was smoother and more uniform, with fewer shell-like structures and surface pores. Conversely, samples made using the standard technique exhibited larger pores (shell-like features) on the concrete surfaces, likely associated with air pockets around expanded clay particles and a less consistent cement film. **Figure 4** illustrates a comparison between the surfaces of samples produced by the two different methods.

As can be seen in **Figure 4** b, the suspension concrete sample has a denser and smoother surface. The pores on this sample are much smaller and less numerous than on a concrete sample prepared using the traditional method (on the left). This indicates a better filling of the mold and distribution of the mortar in the suspension concrete, which correlates with its increased average density and strength.

a) b)

Figure 4 – Comparison of the surface of expanded clay concrete samples: (a) specimen No. 1, mixing according to GOST; (b) specimen No. 2, suspension mixing (author's materials).

The results suggest that the mixing order of the ingredients has a significant impact on the structure and properties of expanded clay concrete. Using the "suspension concrete" method of mixing ensures more efficient usage of cement and enhanced adhesion of the cement paste to the porous aggregate.

It should be noted that the increased strength is achieved without changing the composition of the concrete mixture, that is, by optimizing the mixing process and not increasing the cement content or adding expensive additives. This difference is most noticeable after a longer period of hardening, ranging from 7 to 28 days, which suggests an improvement in the structure of the cement matrix and the contact area with expanded clay using suspension technology.

The practical conclusion from this study is that, when producing expanded clay concrete or other lightweight concrete, it is important to pay attention not only to selecting the optimal composition but also to improving mixing technology. The suspended mixing method has proven to

be an effective way to increase the strength and quality of lightweight concrete without adding additional material costs. This improvement in surface density (fewer voids) is important for manufacturing architectural and decorative elements, such as wall panels, which require high standards of appearance and uniformity.

5 CONCLUSIONS

It has been experimentally proven that changing the order of mixing the components of concrete significantly affects the properties of expanded clay concrete.

1. The suspension mixing method provides higher compressive strength at all stages of hardening compared to the traditional method. On the 28th day, the strength gain was up to 19%.

2. The density of the concrete mixture and finished samples was comparable in both methods, but with the suspension method a more homogeneous structure and stable characteristics were observed.

3. Visual and technological indicators, such as workability and surface quality, demonstrate the advantage of the suspension method.

4. In terms of sustainable development, using the "suspension concrete" method can reduce cement consumption, waste, and increase durability, while also allowing for the use of local raw materials.

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RESEARCH ARTICLE

DEVELOPMENT OF A MATHEMATICAL MODEL OF HEAT TRANSFER THROUGH A MULTILAYER ENCLOSING STRUCTURE WITH AIR LAYERS

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Abstract. *A mathematical model of heat transfer in an innovative external building enclosure, comprising both ventilated and non-ventilated air layers, has been developed in this study. The structural complexity of the considered system necessitates the simultaneous consideration of all three modes of heat transfer: thermal conductivity (conductive transfer), convection, and thermal radiation. The model incorporates boundary conditions on both the interior and exterior surfaces of the enclosure, allowing for the influence of climatic factors and building operation conditions to be taken into account. For the conductive heat transfer, the thermal characteristics of the enclosure layers are assigned based on the physical and mechanical properties of the construction materials. For the layer consisting of a fully enclosed air gap, the model uses the equivalent thermal conductivity value that accounts for heat transfer in a stationary gas medium. In the case of the ventilated air layer, the energy equation is applied to describe the heat exchange processes involving moving air, including the interaction between the airflow and bounding surfaces. As a result, a mathematical model in the form of a system of heat transfer equations adapted to the multilayer structure of the enclosure has been constructed, accompanied by the appropriate boundary conditions. This enables accurate simulation of temperature fields and heat flows depending on the parameters of the construction and the external environment. The developed model can be used in engineering calculations for design tasks, thermal optimization, energy audits, and evaluation of the efficiency of various enclosure systems. Furthermore, the model can be integrated into building information modeling (BIM) software and used in energy efficiency certification systems. The presented results contribute to improving approaches to analyzing the thermal behavior of building structures and to the development of sustainable construction principles.*

Keywords: *mathematical model, heat transfer, multilayer enclosure, air layer, boundary conditions.*

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АУА ҚАБАТТАРЫ БАР КӨП ҚАБАТТЫ ҚОРШАУ КОНСТРУКЦИЯСЫ АРҚЫЛЫ ЖЫЛУ ӨТКІЗУДІҢ МАТЕМАТИКАЛЫҚ МОДЕЛІН ЖАСАУ

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Аңдатпа. *Бұл жұмыста бір мезгілде желдетілетін және желдетілмейтін ауа қабаттары бар сыртқы инновациялық қоршау конструкциясындағы жылу алмасудың математикалық моделі әзірленді. Қарастырылып отырған жүйенің конструктивтік күрделілігі жылу алмасудың үш механизмі – жылуөткізгіштік (кондуктивті тасымалдау), конвекция және сәулелік жылу алмасуды – бір уақытта ескеруді талап етеді. Модельде қоршау конструкциясының ішкі және сыртқы беттерінде шекаралық шарттар берілген, бұл климаттық факторлар мен ғимараттың пайдалану жағдайларының әсерін есепке алуға мүмкіндік береді. Кондуктивті жылуөткізгіштікті сипаттау кезінде қоршау қабаттарының жылутехникалық сипаттамалары құрылыс материалдарының физика-механикалық қасиеттеріне сәйкес қабылданады. Толық жабық ауа қабатынан тұратын қабат үшін модельде қозғалмайтын газ ортасындағы жылу беруді ескеретін эквивалентті жылуөткізгіштік мәні қолданылады. Ал желдетілетін ауа қабаты үшін жылу алмасу процестерін, оның ішінде ауа ағыны мен шекаралық беттердің арасындағы өзара әрекеттесуді сипаттау үшін энергия теңдеуі қолданылады. Нәтижесінде көпқабатты қоршау құрылымына бейімделген және сәйкес шекаралық шарттармен толықтырылған жылу тасымалдау теңдеулерінің жиынтығы түріндегі математикалық модель әзірленді. Бұл температуралық өрістер мен жылу ағындарын конструкция параметрлері мен сыртқы орта жағдайларына байланысты дәл модельдеуге мүмкіндік береді. Дайындалған модель жобалау, жылутехникалық оңтайландыру, энергия аудиті және әртүрлі қоршау шешімдерінің тиімділігін бағалау есептерінде инженерлік есептеулерде қолданылуы мүмкін. Сонымен қатар, модельді ғимараттарды ақпараттық модельдеу (BIM) бағдарламалық кешендеріне біріктіруге және энергия үнемділік сертификаттау жүйелерінде қолдануға болады. Ұсынылған нәтижелер құрылыс конструкцияларының жылулық мінез-құлқын талдау тәсілдерін жетілдіруге және орнықты құрылыс қағидаттарын дамытуға ықпал етеді.*

Түйін сөздер: *математикалық модель, жылу беру, көп қабатты қоршау, ауа қабаты, шарттық жағдайлар.*

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НАУЧНАЯ СТАТЬЯ

РАЗРАБОТКА МАТЕМАТИЧЕСКОЙ МОДЕЛИ ТЕПЛОПЕРЕДАЧИ ЧЕРЕЗ МНОГОСЛОЙНУЮ ОГРАЖДАЮЩУЮ КОНСТРУКЦИЮ С ВОЗДУШНЫМИ ПРОСЛОЙКАМИ

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Аннотация. *В работе разработана математическая модель теплопередачи наружного инновационного ограждения, содержащего одновременно вентилируемую и невентилируемую воздушные прослойки. Конструктивная сложность рассматриваемой системы обуславливает необходимость одновременного учёта всех трёх механизмов теплопередачи: теплопроводности (кондуктивной теплопередачи), конвекции и лучистого теплообмена. В разработанной модели заданы граничные условия как на внутренней, так и на наружной поверхности ограждающей конструкции, что позволяет учитывать влияние климатических факторов и условий эксплуатации здания. При описании кондуктивной теплопередачи теплотехнические характеристики слоёв ограждения принимаются в соответствии с физико-механическими свойствами строительных материалов. Для слоя, представляющего собой полностью замкнутую воздушную прослойку, используется величина эквивалентной теплопроводности, учитывающая теплопередачу в неподвижной газовой среде. В случае вентилируемой прослойки в модели используется уравнение энергии, позволяющее описать процессы теплообмена с участием движущегося воздуха, включая взаимодействие между потоком и граничащими поверхностями. В результате построена математическая модель в виде набора уравнений теплопереноса, адаптированных к многослойной структуре ограждения и сопровождаемых соответствующими граничными условиями. Это обеспечивает возможность точного моделирования температурных полей и тепловых потоков в зависимости от параметров конструкции и внешней среды. Разработанная модель может быть использована при инженерных расчётах в задачах проектирования, теплотехнической оптимизации, энергоаудита и оценки эффективности различных ограждающих решений. Также возможна интеграция модели в программные комплексы для информационного моделирования зданий (BIM) и последующее применение в системах сертификации энергоэффективности. Представленные результаты способствуют совершенствованию подходов к анализу теплового поведения строительных конструкций и развитию принципов устойчивого строительства.*

Ключевые слова: *математическая модель, теплопередача, многослойное ограждение, воздушная прослойка, граничные условия.*

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CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

АЛҒЫС/ҚАРЖЫЛАНДЫРУ КӨЗІ

Зерттеу Қазақстан Республикасы Ғылым және жоғары білім министрлігі Ғылым комитетінің гранттық қаржыландыруы аясында (жоба № AP22782896) «Қазақстанның климаттық жағдайын және динамикалық жүктемелерді ескере отырып ғимараттардың энергия үнемдейтін сыртқы қабырға конструкцияларын әзірлеу» тақырыбы бойынша жүргізілді.

МҮДДЕЛЕР ҚАҚТЫҒЫСЫ

Авторлар мүдделер қақтығысы жоқ деп мәлімдейді.

БЛАГОДАРНОСТИ/ИСТОЧНИК ФИНАНСИРОВАНИЯ

Исследование проведено в рамках грантового финансирования Комитета науки Министерства науки и высшего образования Республики Казахстан (проект № AP22782896) по теме: «Разработка энергоэффективных наружных стеновых конструкций зданий с учетом динамических воздействий в условиях регионов Казахстана».

КОНФЛИКТ ИНТЕРЕСОВ

Авторы заявляют, что конфликта интересов нет.

1 INTRODUCTION

The development of new energy-efficient multilayer building envelope structures is currently among the most prominent trends at the international level.

To address this issue, the scientific and engineering community is investigating various innovative structural solutions in the field of external enclosures. The relevance of this direction is driven by heat losses through building envelopes, where thermal energy consumption can reach up to 40%, simultaneously causing both economic and environmental concerns.

Given that building envelopes play a key role in establishing indoor climatic parameters, it is feasible to utilize an adaptive structural system, in which a two-channel air layer is proposed as an innovative solution. This configuration has a positive impact on thermal energy savings during both the winter and summer seasons. However, due to the technical complexity and the payback of economic investments – where cost increases reach nearly 50% – the practical implementation of such systems at the national level in the Republic of Kazakhstan presents certain challenges.

The use of double-skin glass façades equipped with integrated movable shading devices significantly enhances the energy performance of buildings, particularly in comparison to opaque walls. As an adaptive solution for moisture removal in multilayer external enclosures, the incorporation of ventilated air channels into the envelope structure is feasible, providing high thermal insulation properties for the panels and resulting in substantial energy savings.

Given the above circumstances, the development of new energy-efficient structures is currently being pursued actively, employing various research methods ranging from experimental studies to finite element modeling using modern software platforms.

Accordingly, the objective of this study is to develop a mathematical model of heat transfer through a new energy-efficient multilayer building envelope with air layers, which will subsequently enable the application of the developed model in theoretical calculations and engineering analysis.

2 LITERATURE REVIEW

The studies by **Xian et al. (2025)** and **Manzueta et al. (2024)** demonstrate that external building envelope structures account for a significant share of heat loss in buildings, highlighting the need for new technological solutions.

In the research conducted by **Astorqui & Porras-Amores (2017)**, as well as **Dimoudi et al. (2004)**, façade systems with double air chambers are examined, where the movement of air masses is controlled.

The positive effect of a ventilated air layer in combination with dynamic insulation layers is also noted by **Pasquay (2004)**, with evidence demonstrating reduced cooling costs for buildings during warm seasons.

An analysis of the efficiency of double-glazed glass façades with integrated movable shading elements is presented in the studies by **Baldinelli (2009)** and **Bessoudo et al. (2010)**. Such solutions are capable of enhancing the energy performance of buildings throughout their entire service life.

The studies by **Nizovtsev et al. (2020)** and **Gagliano & Aneli (2020)** emphasize the importance of ventilated channels in multilayer panels, which not only effectively remove moisture but also maintain stable thermal insulation characteristics under conditions of high humidity.

Mathematical modeling of heat transfer through multilayer structures with air gaps is examined in the work of **Zhangabay et al. (2023)**, where the efficiency of heat-reflecting screens was analyzed using the ANSYS software package.

3 MATERIALS AND METHODS

In this study, a model of an energy-efficient external wall structure featuring both ventilated and non-ventilated air layers has been developed. Traditional calculation methods for determining heat transfer, as presented in the regulatory document **(SP RK 2.04-107-2022)**, are found to be

inapplicable due to the presence of an additional enclosed air layer, which serves as a novel structural solution **(SP RK 2.04-107-2022, 2022)**. Consequently, there is a need for the initial development of a mathematical model of such a structure for further research.

To achieve this goal, the geometric and thermal characteristics of the studied structure are presented in Figure 1 and Table 1. Boundary conditions related to indoor microclimate parameters and external climatic influences may subsequently be adopted in accordance with relevant standards **(SP RK 2.04-01-2017, 2017; GOST 30494-2011, 2011)**.

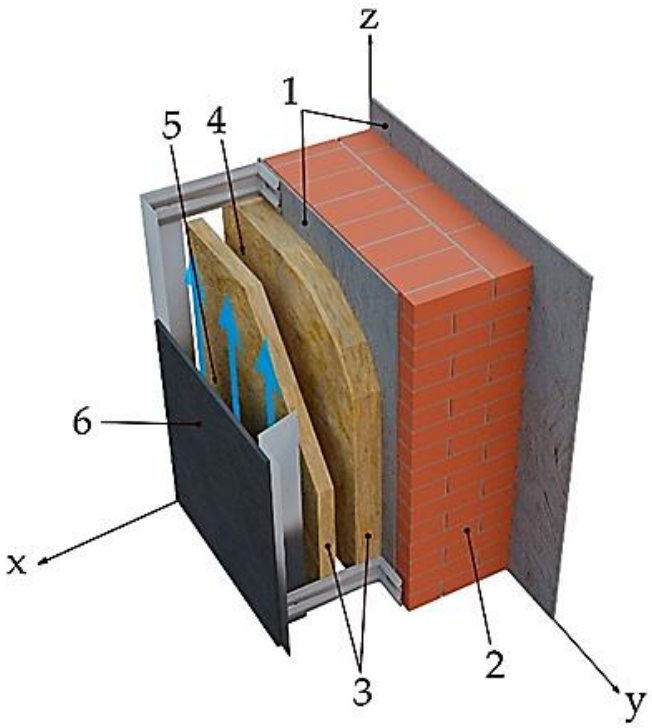

Figure 1 – Multilayer structure of the external building envelope

Table 1

Thermal characteristics of the layers of the multilayer external building envelope structure **(SP RK 2.04-107-2022, 2022)**.

Layer number	Description	Density, kg/m³	Thermal conductivity coefficient, W/(m·°C)	Vapor permeability, mg/(m·h·Pa)
1	Cement-sand plaster	1800	0,76	0,09
2	Masonry of ceramic bricks	1400	0,58	0,14
3	Extruded polystyrene foam or basalt wool insulation with a density of not less than 110 kg/m³	25	0,03-0,035	0,005
4	Enclosed air cavity	–	–	–
5	Ventilated air cavity	–	–	–
6	Porcelain stoneware	2800	3,49	0,008

4 RESULTS AND DISCUSSION

When constructing the mathematical model of heat transfer through the considered multilayer building envelope structure, the layers are described as homogeneous isotropic media with an equivalent thermal conductivity. This conductivity accounts for conductive, convective, and radiative components of heat transfer through the respective layer of the envelope structure. Such an approach allows the heat transfer problem to be considered in a one-dimensional steady-state formulation.

Let the spatial x-axis be directed from the interior toward the exterior, with the origin placed at the inner surface of the building envelope. Then, introducing the notation δ_i for the thickness of the *i*-th layer of the envelope structure, the following expressions can be written:

$$x_0 = 0,\ x_k = \sum_{i=1}^{k} \delta_i\,,\ x_n = \sum_{i=1}^{n} \delta_i\,, \tag{1}$$

For each layer, except for the ventilated air cavity, the one-dimensional linear steady-state heat conduction equation can be written.

$$\lambda_k \frac{\partial^2 T}{\partial x^2} = 0, \qquad x_{k-1} < x < x_k, \qquad k = 1,\ldots n\,, \tag{2}$$

At the interface between layers, due to the ideal thermal contact, the conditions describing the continuity of temperature and heat flux are satisfied:

$$T\big|_{x=x_k-0} = T\big|_{x=x_k+0}, \qquad k = 1,\ldots n-1, \tag{3}$$

$$\lambda_k \left.\frac{\partial T}{\partial x}\right|_{x=x_k-0} = \lambda_{k+1} \left.\frac{\partial T}{\partial x}\right|_{x=x_k+0}, \qquad k = 1,\ldots n-1. \tag{4}$$

Convective heat exchange between the building envelope and the surrounding air environment is described by the following boundary conditions:

on the inner surface of the building envelope

$$\lambda_1 \left.\frac{\partial T}{\partial x}\right|_{x=0} = \alpha_{\text{int}}\left(T\big|_{x=0} - T_{\text{int}}\right), \tag{5}$$

on the outer surface of the building envelope

$$\lambda_n \left.\frac{\partial T}{\partial x}\right|_{x=x_n} = \alpha_{ext}\left(T\big|_{x=x_n} - T_{ext}\right). \tag{6}$$

To simplify subsequent expressions, the following notations are introduced:

$T_0 = T(0)$ – temperature at the inner surface of the building envelope;

$T_k = T(x_k)$ – temperature at the interface between layers numbered x_k and x_{k+1};

$T_n = T(x_n)$ – temperature at the outer surface of the building envelope.

The thermal conductivity coefficients for the layers without air cavities are assigned based on the initial data provided in Table 1.

For a layer consisting entirely of a closed air cavity, the equivalent thermal conductivity value must be used in equations (2) in place of λ_k. Let us denote this as $\lambda_{э.в.k}$.

Since the equivalent thermal conductivity implies a homogeneous isotropic medium, the heat flux density in the *x*-direction can be written as:

$$q = -\lambda_{э.в.k} \frac{\partial T}{\partial x}\,. \tag{7}$$

Due to the one-dimensional nature of the problem and the absence of internal heat sources, the partial derivative of temperature with respect to the spatial coordinate in expression (7) can be accurately represented as a finite difference, which allows expression (7) to be rewritten in the following form:

$$q = -\lambda_{э.в.k}\frac{T_k - T_{k-1}}{\delta_k} = \lambda_{э.в.k}\frac{T_{k-1} - T_k}{\delta_k}. \quad (8)$$

On the other hand, when considering the air cavity, the heat flux can be represented as the sum of two components – conductive-convective and radiative:

$$q = q_к + q_л. \quad (9)$$

According to **Lykov (1978)** and **Kutateladze (1990)**, in vertical air cavities between flat surfaces, conductive-convective heat transfer under natural convection conditions can be adequately described by mathematical models for stationary layers, using the concept of an effective thermal conductivity coefficient λ_k, which is defined as follows:

$$\begin{aligned} \lambda_к &= \lambda_в \quad \text{at} \quad Ra < 104, \\ \lambda_к &= \lambda_в \cdot 0{,}062 \cdot Ra^{1/3} \quad \text{at} \quad 10^4 < Ra < 10^4, \\ \lambda_к &= \lambda_в \cdot 0{,}22 \cdot Ra^{1/4} \quad \text{at} \quad 10^7 < Ra < 10^{10}, \end{aligned} \quad (10)$$

where $Ra = \frac{g\delta^3\beta\Delta T}{\nu}Pr$

The values of $\lambda_в$, ν and Pr expression (10) are taken at the averaged temperature and pressure within the air cavity.

Thus

$$q_к = -\lambda_к\frac{\partial T}{\partial x}. \quad (11)$$

The radiative component of the heat flux density, according to a number of studies, can be determined from the corresponding expression **(Zhangabay et al., 2023a; Zhangabay et al., 2023b; Zhangabay et al., 2024)**.

$$q_л = \varepsilon\sigma_0(T_{k-1}{}^4 - T^4_k), \quad (12)$$

Substituting (8), (11), and (12) into (9) and using the same finite difference representation of the temperature partial derivative for (13) as in (8), we obtain:

$$\lambda_{э.в.k}\frac{T_{k-1} - T_k}{\delta_k} = \lambda_к\frac{T_{k-1} - T_k}{\delta_k} + \varepsilon\sigma_0\left(T^4_{k-1} - T^4_k\right), \quad (13)$$

from which we obtain

$$\lambda_{э.в.k} = \lambda_к + \frac{\delta_k\varepsilon\sigma_0\left(T^4_{k-1} - T^4_k\right)}{T_{k-1} - T_k}. \quad (14)$$

To formulate the mathematical model of heat exchange in the ventilated air cavity, the energy equation is used, which in the general multidimensional unsteady case can be written as:

$$c\rho\frac{dT}{d\tau} = \lambda\Delta T + q_V, \quad (15)$$

In the ventilated air cavity, a clearly defined upward airflow is formed, with the absence of local vortices. Given the negligible viscous effects in the boundary layers near the walls enclosing the

cavity, the air velocity can be assumed to be uniform across the cross-section of the cavity. Moreover, since the air temperature changes insignificantly along the flow direction within the cavity, the compressibility of air can be neglected in the energy equation, and its density can be considered constant.

Therefore, given that the air mass flow rate is constant, the air velocity can be assumed to be constant at every point within the ventilated cavity. In this case, by expressing the total time derivative in equation (15) through partial time derivatives, the one-dimensional steady-state form of the equation can be written as:

$$c\rho v\frac{\partial T}{\partial z}=\lambda\frac{\partial^2 T}{\partial z^2}+q_V, \tag{16}$$

The volumetric density of internal heat sources is defined based on the heat balance of the fluxes passing through the walls enclosing the cavity: the amount of heat entering an elementary volume of air in the cavity is equal to the difference between the amount of heat received from the indoor side and the amount of heat transferred through the outer cladding to the surrounding environment:

$$\delta Q_V=\delta Q_{int}-\delta Q_{ext}, \tag{17}$$

For an elementary volume of size $\delta_k\times\delta L\times\delta z$ (where δ_k is the thickness of the cavity, and δL and δz are the dimensions of the elementary volume in the horizontal and vertical directions, respectively), equation (17) can be written as:

$$q_V\cdot\delta_k\cdot\delta L\cdot\delta z=\alpha_п\cdot\delta L\cdot\delta z\,(T_{k-1}-T(z))-\alpha_п\cdot\delta L\cdot\delta z\,(T(z)-T_k), \tag{18}$$

From relation (18), we obtain the expression for the specific volumetric density of internal heat sources.

$$q_V=\frac{\alpha_п}{\delta_k}\left(T_{k-1}+T_k-2T(z)\right), \tag{19}$$

Since in the considered mathematical model the air velocity in the ventilated air cavity remains constant with height, and the temperature of the cavity's bounding walls is assumed to be constant, it follows from (18) that the air in the cavity heats up uniformly at every point. Consequently, the temperature distribution $T(z)$ is a linear function of the vertical coordinate. Therefore, the second derivative of air temperature with respect to the vertical coordinate is equal to zero, and equation (16), taking into account (19), can be rewritten as:

$$c\rho v\frac{dT}{dz}=\frac{\alpha_п}{\delta_k}\left(T_{k-1}+T_k-2T(z)\right), \tag{20}$$

The initial condition for equation (20) is defined based on the fact that at the lowest point of the air cavity, air inflow occurs, and its temperature is equal to the ambient air temperature:

$$T(0)=T_{ext}, \tag{21}$$

The value of the heat transfer coefficient α_p can be obtained from well-known empirical correlations for a flat channel **(Lykov, 1978; Kutateladze, 1990; Isachenko, Osipova, and Sukomel, 1975)**:

$$\mathrm{Nu}=\mathrm{Nu}(\mathrm{Re},\mathrm{Pr}), \tag{22}$$

where $\mathrm{Nu}=\alpha_п/(\delta_k\cdot\lambda)$.

The solution of the ordinary differential equation (20) with the initial condition (21) has the following form:

$$T(z) = \left[T_{\text{ext}} - \frac{T_{k+1} + T_k}{2} \right] \cdot \exp\left(- \frac{2\alpha_{\text{п}}}{\delta_{\text{k}} c\rho v} z \right) + \frac{T_{k+1} + T_k}{2}. \quad (23)$$

The average air temperature in the ventilated cavity can be determined as the mean integral value over the height:

$$T_{\text{п}} = \frac{1}{H} \int_0^H T(z)dz = \frac{1}{H} \left[1 - \frac{T_{\text{ext}} - \frac{T_{k+1} + T_k}{2}}{2\alpha_{\text{п}}} \delta_{\text{k}} c\rho v \cdot \exp\left(- \frac{2\alpha_{\text{п}}}{\delta_{\text{k}} c\rho v} H \right) \right], \quad (24)$$

The air temperature at the outlet of the ventilated cavity is obtained from expression (23) at $z = H$:

$$T_{\text{out}} = \left[T_{\text{ext}} - \frac{T_{k+1} + T_k}{2} \right] \cdot \exp\left(- \frac{2\alpha_{\text{п}}}{\delta_{\text{k}} c\rho v} H \right) + \frac{T_{k+1} + T_k}{2}, \quad (25)$$

The air velocity in the ventilated cavity can be determined based on the balance between the total pressure losses in the ventilated air cavity and the driving pressure (natural draught), which is caused by Archimedean forces arising due to the difference in air density within the ventilated cavity and at its outlet:

$$\Delta p^{\text{o}} = p_{\text{c}}, \quad (26)$$

Neglecting the pressure losses at the inlet and outlet, equation (26) for a flat vertical slot channel can be rewritten as:

$$\xi(H/2\delta_k)\rho_{\text{п}} v^2/2 = (\rho_{\text{ext}} - \rho_{\text{out}})gH, \quad (27)$$

The air density at a given temperature in equation (27) can be obtained from the Clapeyron-Mendeleev equation:

$$\rho_i = p_i/(RT_i), \quad (28)$$

In which the thermodynamic pressure p_i can be taken as 1 atm.
The heat flux balance within the cavity is described by the law of conservation of energy: the amount of heat entering the ventilated air cavity from the interior side Q_{int} is equal to the sum of the heat carried away by the ventilation air Q_{out}, the heat transferred by convection from the air cavity to the outer cladding Q_{ext},, and the heat transferred by radiation from the inner wall of the cavity to the outer wall $Q_{\text{л}}$:

$$Q_{\text{int}} = Q_{\text{out}} + Q_{\text{ext}} + Q_{\text{л}}. \quad (29)$$

For a unit length δL of the building envelope in the horizontal direction, these quantities can be expressed as:

$$Q_{\text{int}} = \alpha_{\text{п}}(T_{k-1} - T_{\text{п}}) \cdot H \cdot \delta L;\ Q_{\text{ext}} = \alpha_{\text{п}}(T_{\text{п}} - T_k) \cdot H \cdot \delta L; \quad (30)$$
$$Q_{\text{out}} = v\ \rho \cdot \delta_k \cdot \delta L \cdot c \cdot (T_{\text{out}} - T_{\text{ext}});\ Q_{\text{л}} = \varepsilon \cdot \sigma_0 \cdot (T_{k-1}{}^4 - T_k^4) \cdot H \cdot \delta L.$$

Substituting (30) into (29), we obtain:

$$\alpha_{\text{п}}(T_{k-1} - T_{\text{п}}) \cdot H = \alpha_{\text{п}}(T_{\text{п}} - T_k) \cdot H + v\ \rho \cdot \delta_k \cdot c \cdot (T_{\text{out}} - T_{\text{ext}}) + \varepsilon \cdot \sigma_0 \cdot (T_{k-1}{}^4 - T_k^4) \cdot H. \quad (31)$$

Thus, the mathematical model of the heat transfer phenomenon through the building envelope is described by the following set of equations:

1. For all layers except the ventilated air cavity, the heat flux is determined by equation (8). In this case, the thermal conductivity coefficient in equation (8) is either the corresponding thermophysical property of the material (for a solid layer) or the equivalent thermal conductivity coefficient calculated using formula (14).
2. Equations (24), (25), (27), (28), and (31) for the ventilated air cavity.
3. Boundary conditions (5), (6).

This mathematical model allows determining the temperature distribution T_k at the interfaces between layers, the air temperature within the ventilated cavity $T_{\text{п}}$, the outlet air temperature T_{ou}, and the air velocity in the ventilated cavity v. The temperature within each layer is found through linear approximation based on the temperatures T_k.

5 CONCLUSIONS

1. A mathematical model of heat transfer in an innovative external envelope structure featuring both ventilated and non-ventilated air layers has been developed.
2. The proposed model, due to its structural characteristics, takes into account all three modes of heat transfer: conductive, convective, and radiative.
3. Boundary conditions were defined for both the interior and exterior surfaces of the building envelope.
4. In modeling conductive heat transfer, the thermal properties were assigned according to the characteristics of the construction materials. For the layer consisting entirely of a closed air gap, the model utilizes an equivalent thermal conductivity value, while for the ventilated component of the envelope, the heat exchange model employs the energy equation.
5. As a result, a set of equations was developed that incorporates the boundary conditions, enabling accurate description of the external envelope structure and allowing the model to be applied in future calculation methodologies.

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RESEARCH ARTICLE

MULTIFACTOR ASSESSMENT OF HYDRAULIC STRUCTURES IN SEISMICALLY ACTIVE ZONES: A CASE STUDY OF THE TASOTKEL RESERVOIR, REPUBLIC OF KAZAKHSTAN

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Abstract. *This article presents a multifactor assessment of the technical condition of the Tasotkel Dam, located in the seismically active zone of southern Kazakhstan. With the increasing frequency and intensity of earthquakes in the region - including the March 28, 2025, earthquake near the village of Merke in the Zhambyl region - there is a growing need for a systematic approach to evaluating the seismic safety of hydraulic structures. The investigation employed a range of modern techniques, including visual inspection, instrumental monitoring, geodetic surveying, non-destructive testing of concrete structures, as well as laboratory and in-situ analysis of the physical and mechanical properties of the dam body and its foundation soils. The assessment revealed localized defects in the facing, signs of erosion, reduced piezometric levels compared to design values, and high filtration activity of the foundation. Geodetic data confirmed the absence of critical deformations but identified areas of potential instability. Based on the collected engineering data, a numerical model of the dam was developed using the Plaxis 2D software package. Slope stability calculations were performed for two key cross-sections (PK 5+00 and PK 12+00) under seismic loading scenarios corresponding to intensities of 7 and 8 on the MSK-64 scale. As a result, safety factors, potential failure surfaces, filtration flow directions, and pore pressure distributions were identified. The study revealed the necessity for reconstruction and seismic strengthening of certain dam sections. The findings underscore the importance of implementing a multifactor approach as a reliable diagnostic tool in conditions of elevated seismic risk.*

Keywords: *hydraulic structures, seismic stability, dam, multifactor assessment, numerical modeling.*

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MULTIFACTOR ASSESSMENT OF HYDRAULIC STRUCTURES IN SEISMICALLY ACTIVE ZONES: A CASE STUDY OF THE TASOTKEL RESERVOIR, REPUBLIC OF KAZAKHSTAN

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Аңдатпа. *Бұл мақала Қазақстанның оңтүстігінде орналасқан сейсмикалық қауіпті аймақтағы Тасөткел су торабының техникалық жағдайына көпфакторлы зерттеу жүргізуге арналған. Аймақта жер сілкіністерінің жиілігі мен қарқындылығының артуына, соның ішінде 2025 жылғы 28 наурызда Жамбыл облысындағы Меркі ауылына жақын жерде болған жер сілкінісіне байланысты, гидротехникалық құрылымдардың сейсмикалық тұрақтылығын бағалауға жүйелі тәсілдің қажеттілігі артып отыр. Зерттеу барысында заманауи әдістер кешені қолданылды: көзбен шолу, аспаптық бақылау, геодезиялық өлшеулер, бетон құрылымдарын бұзбайтын сынау, сондай-ақ су торабының бойындағы мен негізіндегі топырақтардың физика-механикалық қасиеттеріне зертханалық және дала жағдайындағы талдау. Зерттеу нәтижелері бойынша беткі қабаттың жергілікті ақаулары, эрозия белгілері, жобалық мәндермен салыстырғанда пьезометриялық деңгейлердің төмендеуі және іргетастың жоғары сүзгілік белсенділігі анықталды. Геодезиялық деректер айтарлықтай деформациялардың жоқ екенін растады, бірақ әлеуетті орнықсыздық аймақтары белгіленді. Инженерлік деректер негізінде Plaxis 2D бағдарламалық кешенінде су торабының сандық моделі жасалды. Есептеулер негізгі екі қимада (ПК 5+00 және ПК 12+00) 7 және 8 баллдық сейсмикалық әсер сценарийлері үшін жүргізілді (MSK-64 шкаласы бойынша). Нәтижесінде тұрақтылық коэффициенттері, ықтимал опырылу беттері, сүзгілік ағындардың бағыты мен қысым таралуы анықталды. Бұл зерттеу су торабының кейбір учаскелерін қайта құру және сейсмикалық нығайту қажеттілігін көрсетті. Жоғары сейсмикалық қауіптілік жағдайында сенімді диагностикалық әдіс ретінде көпфакторлы тәсілді енгізудің маңыздылығы дәлелденді.*

Түйін сөздер: *гидротехникалық құрылыстар, сейсмикалық тұрақтылық, бөгет, көпфакторлы зерттеу, сандық модельдеу.*

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MULTIFACTOR ASSESSMENT OF HYDRAULIC STRUCTURES IN SEISMICALLY ACTIVE ZONES: A CASE STUDY OF THE TASOTKEL RESERVOIR, REPUBLIC OF KAZAKHSTAN

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Аннотация. *Статья посвящена многофакторному обследованию технического состояния Тасоткельской плотины, расположенной в сейсмически активной зоне юга Казахстана. В условиях увеличения частоты и интенсивности землетрясений в регионе, включая землетрясение 28 марта 2025 года вблизи села Мерке Жамбылской области, возрастает потребность в системном подходе к оценке сейсмостойкости гидротехнических сооружений. Обследование выполнено с применением комплекса современных методов: визуального осмотра, инструментального контроля, геодезических наблюдений, неразрушающего контроля бетонных конструкций, а также лабораторного и натурного анализа физико-механических свойств грунтов тела плотины и её основания. По результатам обследования установлены локальные дефекты облицовки, признаки эрозии, снижение пьезометрических уровней по сравнению с проектными значениями и высокая фильтрационная активность основания. Геодезические данные подтвердили отсутствие критических деформаций, однако зафиксированы зоны потенциальной нестабильности. На основе полученных инженерных данных была построена модель плотины в программном комплексе Plaxis 2D, в рамках которой проведены численные расчёты устойчивости низового откоса на двух ключевых поперечниках (ПК 5+00 и ПК 12+00). Моделирование выполнено для различных сценариев сейсмической нагрузки (7 и 8 баллов по шкале MSK-64). В результате определены коэффициенты устойчивости, потенциальные поверхности обрушения, направления фильтрационных потоков и распределение фильтрационного давления. Проведённое исследование выявило необходимость реализации мероприятий по реконструкции и сейсмоусилению отдельных участков плотины.*

Ключевые слова: *гидротехнические сооружения, сейсмическая устойчивость, плотина, многофакторное обследование, численное моделирование.*

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CONFLICT OF INTEREST

The authors state that there is no conflict of interest

АЛҒЫС / ҚАРЖЫЛАНДЫРУ КӨЗІ

Зерттеу Қазақстан Республикасы Ғылым және жоғары білім министрлігі Ғылым комитетінің № AP23487624 ғылыми жобасы аясында қаржылық қолдауымен орындалды.

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КОНФЛИКТ ИНТЕРЕСОВ

Авторы подтверждают, что конфликта интересов нет.

1 INTRODUCTION

Dams are among the most critical and complex hydraulic structures built across rivers to create reservoirs that serve essential functions such as flow regulation, flood control, water supply for domestic and industrial needs, irrigation of agricultural lands, and hydroelectric power generation. The safety and reliability of dams depend directly on their resistance to external loads, including hydrostatic pressure, wind forces, and seismic activity-especially in regions with high seismic risk.

In recent years, the frequency and intensity of earthquakes have increased globally, including in Kazakhstan. A particularly alarming event occurred on March 28, 2025, when an earthquake struck near the village of Merke in the Zhambyl Region, near the Tasotkel Reservoir. This incident has underscored the urgent need to reassess seismic safety strategies and initiate comprehensive investigations of hydraulic structures located in seismically active zones.

The analysis of the technical inspection report on the Tasotkel Reservoir revealed serious deficiencies in the existing practice of inspecting hydraulic structures in Kazakhstan. Many inspections are carried out superficially and formally, without the use of modern methods, computational models, or scientifically grounded approaches. This has raised valid concerns within the scientific community and highlights the need to revise the current regulatory framework and technical guidelines governing the assessment and maintenance of dams and reservoirs. The development of new methodological standards that ensure comprehensive and reliable evaluations is now more crucial than ever.

Against this backdrop, multifactor assessments gain particular importance. These assessments consider the full spectrum of influencing parameters: engineering-geological conditions, current technical state, deformation dynamics, filtration and sedimentation levels, as well as the seismic vulnerability of structures. Unlike one-time visual inspections, a multifactor approach involves the application of geophysical techniques, instrumented monitoring, engineering modeling, and digital technologies, allowing for a comprehensive and objective evaluation of a structure’s condition.

Commissioned in 1974, the Tasotkel Reservoir is a strategically significant facility in the water management system of southern Kazakhstan. It provides irrigation for more than 35,000 hectares of agricultural land in the Shu and Moiynkum districts, supplies water to the Tasotkel Hydropower Plant and maintains ecological flow in the downstream section of the Shu River. The reliable operation of the dam is directly linked to regional food security, sustainable development of the agro-industrial sector, and overall social stability.

Figure 1 shows a satellite image fragment depicting the Tasotkel Reservoir area, including its boundaries, adjacent irrigation zones, and key hydraulic structures. The image was obtained using remote sensing technologies and provides a clear visualization of the reservoir’s scale, hydrographic position, and spatial relationships with the surrounding infrastructure.

The region’s harsh continental and arid climate, complex hydrogeology, and increasing seismic activity necessitate a reassessment of existing engineering solutions. According to the General Seismic Zoning Map (GSZ–475) and the national construction standard SP RK 2.03–30–2017*, the seismic hazard level at the site has been revised from 6 to 7–8 on the MSK scale, with a calculated horizontal ground acceleration of ag = 0.279g for soil conditions classified as Type II. Combined with the age of the structure and identified defects-such as the undermining of facing slabs on the upstream slope due to wind-driven waves in April 2023-this situation necessitates reconstruction and seismic strengthening measures.

Thus, conducting a scientifically grounded, multifactor comprehensive assessment of the Tasotkel Dam is not merely a technical necessity but a matter of national security, sustainable agricultural production, and disaster prevention. The findings of this study will provide the foundation for updating Kazakhstan's normative and technical documents and for developing new standards for the diagnosis and evaluation of hydraulic structures under increasing seismic threats.

Figure 2 presents a 3D situational plan of the Tasotkel Reservoir, illustrating its spatial position within the river valley, the shoreline configuration, the location of main hydraulic structures, irrigation canals, and infrastructure elements. The model provides a visual representation of the terrain and allows for the assessment of the engineering and geographical features of the study area.

Figure 1 – Satellite image of the Tasotkel Reservoir (https://earth.google.com/)

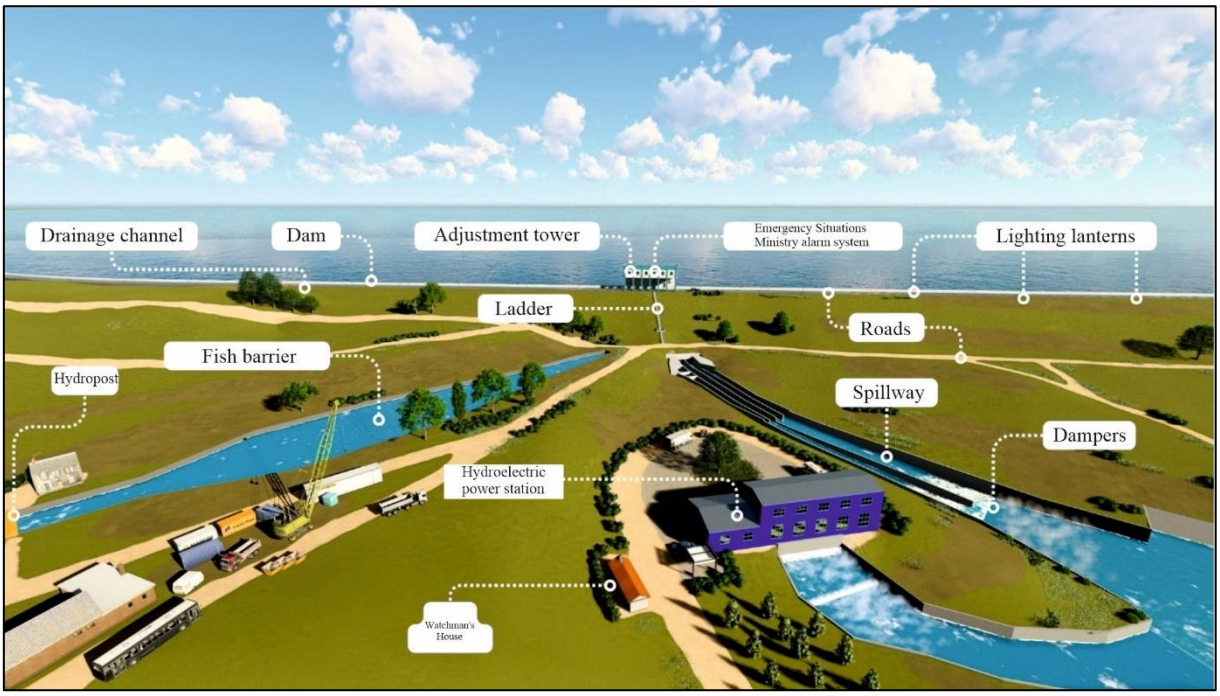

Figure 2 – Situational Plan of the Tasotkel Reservoir

2 LITERATURE REVIEW

The issue of ensuring the reliability of hydraulic structures, especially under seismic conditions, has been addressed in several recent studies. The rapid advancement of digital technologies has significantly improved the accuracy of diagnostics and the ability to predict dam behavior under dynamic loads.

For instance, **Antonovskaya et al. (2015); Antonovskaya et al. (2019)** emphasizes the importance of visual inspection using unmanned aerial vehicles (UAVs), computer vision systems, and artificial intelligence to assess the technical condition of dams. These technologies enable the early detection of hidden defects, cracks, and signs of deformation.

Bathymetric surveys are also becoming an essential element of dam assessments. **Simão Sêco e Pinto (2015)** evaluated sedimentation rates and accumulation patterns at the Obruk Dam in Turkey, allowing them to identify high-risk zones of siltation with precision.

Bonazzi et al. (2025); Gupta (2018) investigated the behavior of coarse-grained materials under seismic loading and developed a numerical method for analyzing residual deformations in rockfill dams-an approach that is critical for predicting long-term structural stability.

Historical events have demonstrated the high vulnerability of hydraulic structures to seismic impacts. Earthquakes in Bhuj (India, 2001), Sichuan (China, 2008), Iwate–Miyagi (Japan, 2008), and the devastating 2011 tsunami that damaged coastal embankments at the Fukushima Nuclear Power Plant illustrate the consequences of insufficient structural diagnostics.

Particular attention must be paid to the series of destructive earthquakes between 2023 and 2025 in Turkey, China, Peru, and Chile, which revealed serious structural damage to dams and reservoirs, including cracks in dam bodies, displacement of slabs, crest loss, and the emergence of groundwater. These incidents highlight the pressing need for international collaboration in the field of dam diagnostics, monitoring, and seismic strengthening.

Hinks (2023); Yiadom et al. (2009) proposed an innovative method of seismic isolation for earth dams using recycled steel-cord tires filled with a rubber-bitumen mix ("gumbrin"), which significantly reduces seismic wave amplitudes.

Green et al. (2023) and **Latrubesse et al. (2020)** applied non-destructive testing and engineering geophysics methods to assess the condition of earth dams at the Shapsug Reservoir. Their findings helped identify zones of potential filtration and led to the development of foundation reinforcement recommendations.

Adamo (2020) presented long-term observation data from the Akdarya Reservoir in Uzbekistan, combining leveling surveys and mathematical modeling. This allowed for a substantiated analysis of structural stability and the calculation of required reconstruction volumes.

A broad range of works by authors such as **Xiang et al. (2022); Gorai et al. (2021); Suwatthikul et al. (2021); Xiang et al. (2023) and Moldamuratov et al. (2021)** are dedicated to the topics of dam reconstruction, seismic resistance, and structural adaptation to evolving environmental conditions.

Using dipole electrical sounding, **Jakiyayev et al. (2023)** identified a reduction in apparent resistivity in the reservoir bed area of the Chirkey Dam, attributed to water saturation processes. These findings have substantial implications for evaluating the filtration status of dam foundations.

Thus, the accumulated scientific and practical experience clearly indicates the need for regular, multifactor, and comprehensive assessments of hydraulic structures, considering the combined impact of natural and anthropogenic processes-particularly in seismically active regions.

3 MATERIALS AND METHODS

As part of the multifactor assessment of the Tasotkel Dam, modern methods were applied to evaluate the technical condition of the hydraulic structure. These included visual inspection, instrumental measurements, geodetic monitoring, non-destructive testing, as well as the analysis of the physical and mechanical properties of soils and the condition of reinforced concrete structures.

Visual inspection was carried out along the entire length of the dam crest (1,200 meters) to identify surface defects, breaches in structural integrity, and signs of deformation processes. Particular attention was given to the following elements:

- condition of the facing slabs on the upstream slope;
- presence of cracks, delamination, and settlements along the crest of the dam;
- integrity and functionality of the reinforced concrete parapet and warning barriers;
- signs of erosion and soil washout near the spillway and drainage components.

During the inspection, two local sections of damaged facing were identified, accompanied by soil washout to a depth of up to 40 cm due to wind wave action. Surface displacement of the turf layer was also observed on the downstream slope.

Instrumental measurements included:

- monitoring of piezometric levels in 13 observation wells (PK 5+5.0; PK 9+10; PK 13+00);
- determination of the position of the phreatic surface (depression curve) at various reservoir water levels;
- control of filtration water levels using drainage wells;
- temperature monitoring of concrete structures.

The results indicated that the actual piezometric levels at PK 5+5.0 and PK 9+10 were 5.0 to 7.2 meters below the design levels, indicating a high drainage capacity of the foundation soils.

Geodetic monitoring was conducted to assess potential vertical and horizontal displacements of the dam body. High-precision total stations and leveling instruments were used (measurement error not exceeding ±1.5 mm per 1 km of double-run leveling). The following activities were carried out:

- leveling of 12 benchmarks along the dam crest;

- repeated measurements of control points on the slopes;
- comparison of current coordinates with archival data from the period 2010–2023.

Non-destructive testing methods were used to evaluate the condition of concrete and reinforced concrete structures, including:

- Ultrasonic testing: measurement of longitudinal wave velocity in the concrete of the parapet and inlet section of the outlet works. Average velocity was 3600–4000 m/s, corresponding to concrete of at least grade B15.
- Schmidt hammer testing: rebound values ranged from 25 to 32 units, confirming the required concrete strength.
- Visual-instrumental defectoscopy: used to detect cracks, voids, and delamination in the protective concrete layer.

Assessment of the soil condition in the dam body and its foundation was based on engineering and geological investigations supplemented by targeted in-situ testing. The following parameters were evaluated:

- internal friction angle: from 24° to 36°;
- cohesion: from 0.01 to 0.4 kg/cm²;
- dry unit weight: 1.51–1.66 g/cm³;
- natural moisture content: over 20%;
- porosity coefficient: 0.699;
- permeability coefficient for loose detrital foundation soils: 35 m/day.

Figure 3 presents fragments documented during the visual and instrumental inspection of the Tasotkel Dam. The images illustrate characteristic defects in the facing slabs, areas of soil washout, and structural elements affected by surface erosion and filtration processes. This visual data confirms the necessity of implementing reconstruction measures and reinforcing specific sections of the dam.

Figure 3 – Inspection Fragmens

The physical and mechanical properties of the foundation and dam body soils used in the engineering calculations for strength and filtration stability are presented in Table 1. These parameters were obtained based on data from engineering and geological surveys, laboratory tests, and field observations, and represent the average values for the main engineering-geological elements of the soil profile.

Table 1
Physical and Mechanical Properties of Soils

Name	Designation	Unit of measurement	Soils of the dam body	Priming prism (gravel soil)	Sandy–gravel soil of the base	Gravel
The weight of the soil of natural moisture	$Y_{ВЛ}$	g/cm^3	2,03	1.91	1,91	2,3
The weight of the soil saturated with water	$Y_{нас}$	g/cm^3	2,06	2.0	2,00	2,5
The modulus of deformation of the soil of natural humidity	E	kN/cm^2	39000	40000	40000	-
Modulus of deformation of soil saturated with water	E	kN/cm^2	20000	30000	30000	40000
Filtration coefficient	$к_ф$	m/day	0,41	32	35	75
The Poisson's ratio	v	-	0,35	0,27	0,27	0,27
Soil adhesion of natural moisture	C	kPa	31	1	-	-
Adhesion of soil saturated with water	C	kPa	24	-	2	1
The angle of internal friction of the soil of natural humidity	φ	°	25	31	-	-
The angle of internal friction of the soil saturated with water	φ	°	18	-	33	40

During the inspection of the Tasotkel Dam, measurements were taken of the water level in the reservoir and the position of the phreatic (depression) curve of the filtration flow.

The measurements were conducted along three cross-sections - at PK 5+5.0, PK 9+10, and PK 13+00 - when the reservoir water level was recorded at 514.85 m (with the normal pool level, NPL, being 519.0 m). The results indicated a significantly low piezometric level, ranging from 5.0 to 7.2

meters below the design values. Only in the downstream toe did the actual position of the depression curve correspond closely to or match the design curve.

A detailed analysis showed the following: at PK 5+5.0, within the berm zone, the piezometric level did not exceed 497.49 m, compared to the design value of 505.80 m; at PK 9+10, the level remained below 498.8 m.

These findings indicate a high drainage capacity of foundation soils relative to the design assumptions. At the observed locations, the actual phreatic surface lies significantly lower than the projected line - by 3.1 to 7.2 meters.

Figure 4 shows the actual position of the phreatic surface at a reservoir level of 514.65 m, the expected profile at NPL 519.0 m, and the maximum allowable position of the depression curve.

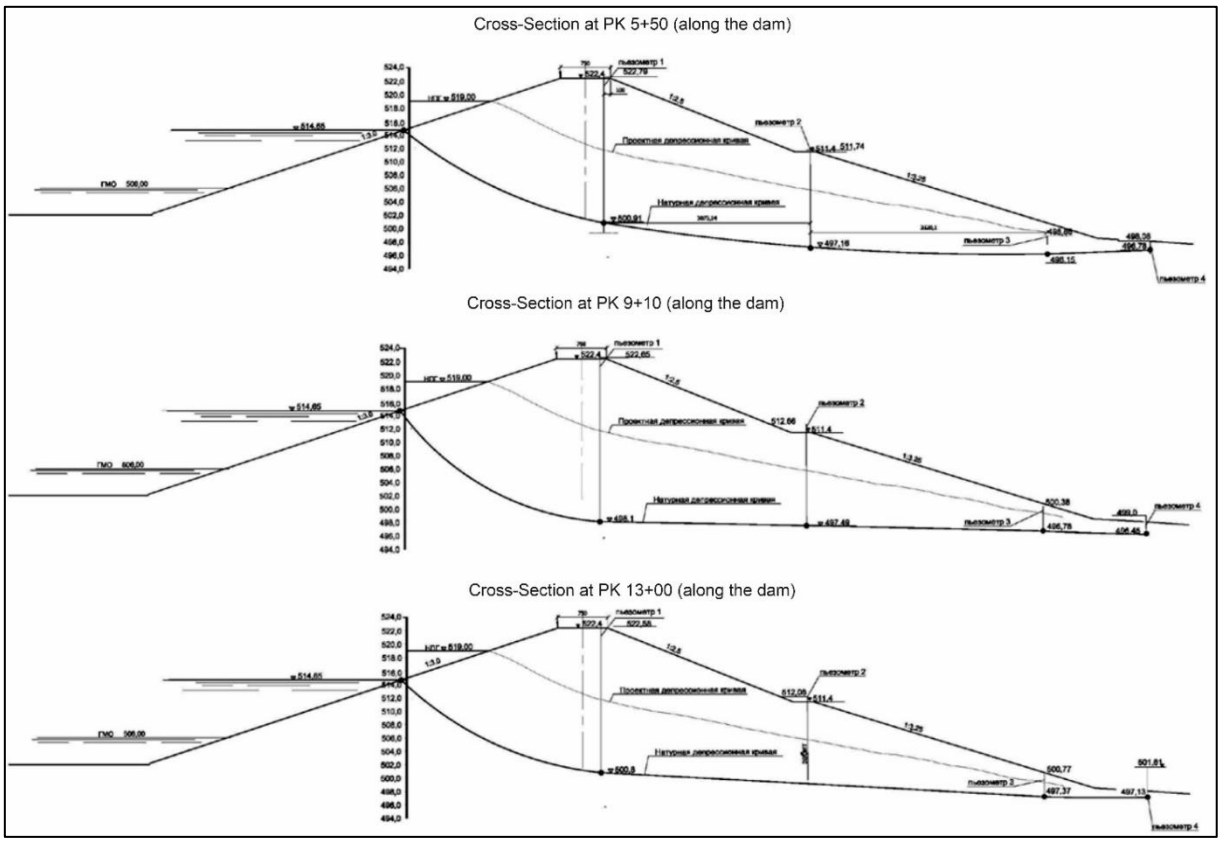

Figure 4 - Position of the Phreatic Surface

4 RESULTS AND DISCUSSION

As part of the engineering assessment, the overall and seismic stability of the downstream slope of the Tasotkel Dam was evaluated for two representative cross-sections - PK 5+00 and PK 12+00. The analysis was carried out using the specialized software Plaxis 2D, a finite element method-based program designed for geotechnical engineering applications, including deformation analysis, slope stability assessment, and groundwater flow modeling.

The modeling process accounted for the stratification of foundation soils, material properties, saturation conditions, and seismic loading. The physical and mechanical properties of soils used in the calculations were based on field and laboratory data obtained from engineering-geological investigations. Real-time measurements of the phreatic surface (depression curve), recorded during the site inspection, were also incorporated.

Figure 5 shows the calculation model for cross-section PK 5+00, including the slope geometry, water levels, outlines of reconstructed sections, the phreatic line at the upstream water level of 519.0 m, and the potential failure surface under seismic loading with an intensity of 8 on the MSK scale.

Figure 6 presents the corresponding model for cross-section PK 12+00, used for evaluating slope stability following the implementation of reinforcement and reconstruction measures. In both cases, seismic conditions were considered in accordance with SP RK 2.03–30–2017* for soil type II, with a design peak ground acceleration of ag = 0.279g.

The calculated safety factor (Fs) was determined for both static and seismic loading conditions. The results demonstrated that:

- Under static conditions, the safety factor exceeded 1.5, meeting regulatory requirements;
- Under seismic conditions with an intensity of 8, the safety factor ranged between 1.1 and 1.2, which is within acceptable limits and confirms the adequacy of the proposed stabilization measures.

These numerical modeling results validate the effectiveness of the design solutions for stabilizing the downstream slope and support the implementation of these technical measures as part of the comprehensive rehabilitation of the dam.

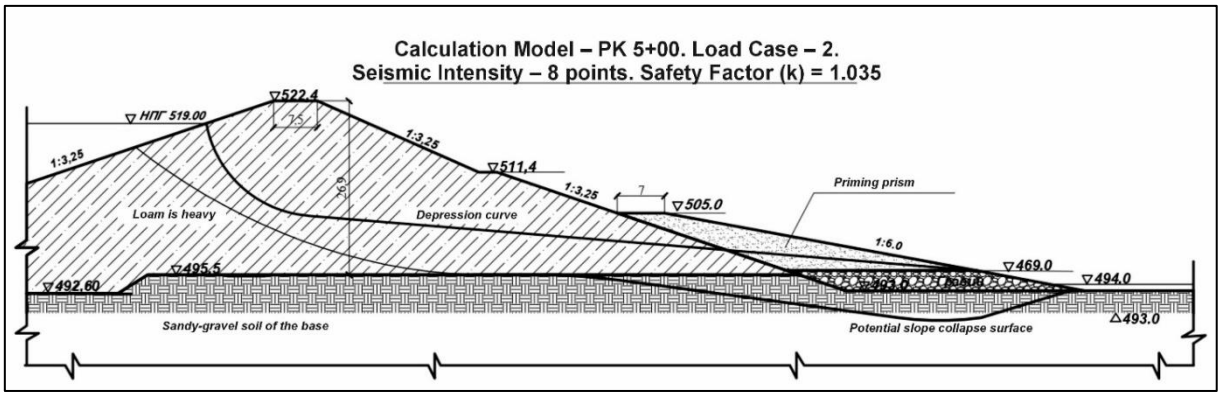

Figure 5 - Calculation Model at Cross-Section PK 5+00

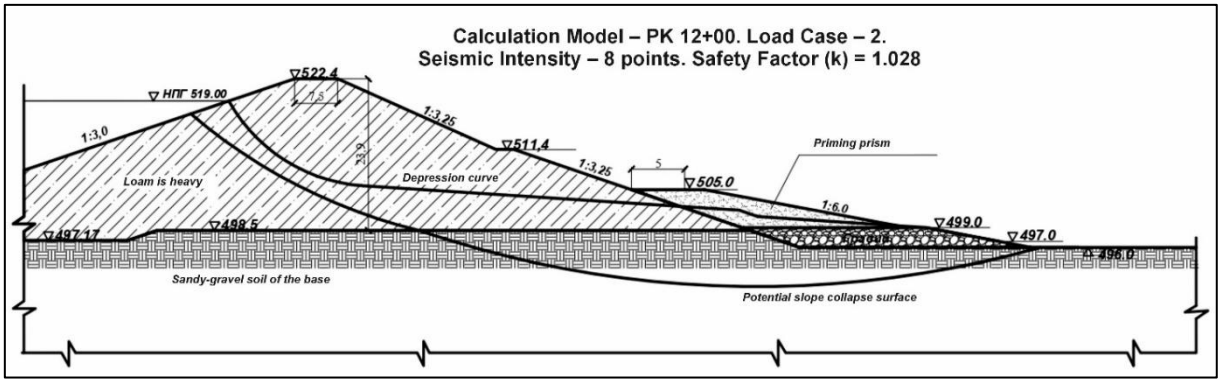

Figure 6 - Calculation Model at Cross-Section PK 12+00

The **Figures 7-18** present the results of numerical modeling performed using the Plaxis 2D software for cross-sections PK 5+00 and PK 12+00, considering seismic loads with intensities of 7 and 8 on the MSK-64 scale.

The models include:

- the geometric configuration of the slopes after reconstruction;

- current data on the position of the phreatic surface at the upstream water level of 519.0 m;
- calculated potential slip (failure) surfaces of the downstream slope;
- values of the safety factor (Fs) under static and seismic loading conditions;
- directions and magnitudes of filtration flow within the dam body.

The simulation results illustrate the slope behavior under different seismic scenarios, including displacements, stress distribution, and critical zones of potential instability. Filtration flows within the dam body and foundation are visualized using a vector field, which allows for the identification of areas with concentrated seepage pressure and the assessment of groundwater movement directions.

Figure 7 presents the calculation schemes for the cross-section at PK 5+00, developed using the Plaxis 2D software under two seismic scenarios. In Load Case 1, with a seismic intensity of 7 points on the MSK-64 scale, the calculated safety factor was k=1.227, indicating a stable slope. In Load Case 2, under 8-point seismic loading, the safety factor decreased to k=1.035, approaching the limit of stability and indicating the need for seismic reinforcement of the downstream slope.

Figure 8 illustrates the phreatic surface position at an upstream water level of 519 m. The configuration of the seepage line allows for the assessment of hydrogeological behavior and the effectiveness of the drainage system under operational conditions.

Figures 9, 10, and **11** show three critical load cases representing the potential failure surfaces of the downstream slope under increasing seismic intensity. **Figure 9** depicts the most probable slip surface formed under moderate saturation and dynamic loading conditions. **Figure 10** highlights stress redistribution within the dam body and potential deformation development in weakened zones. **Figure 11** models a worst-case scenario involving full saturation, maximum seepage, and peak seismic intensity. In all three cases, the safety factors approach minimally acceptable values, requiring further analysis and design measures.

Figure 12 visualizes the seepage flow field within the dam body at PK 5+00. Flow vectors illustrate the direction and magnitude of water movement, allowing the identification of zones with concentrated seepage pressure and potential internal erosion.

Figure 13 presents the calculation schemes for the cross-section at PK 12+00. In Load Case 1 (7-point seismic intensity), the safety factor was k=1.209. Under Load Case 2 (8-point seismic intensity), the safety factor decreased to k=1.028, again indicating the need for slope stabilization under seismic action.

Figure 14 displays the phreatic surface for PK 12+00 at an upstream water level of 519 m. The results highlight specific features of the seepage regime and help evaluate the performance of drainage elements in this section. **Figures 15, 16,** and **17** illustrate additional special seismic load cases at PK 12+00. Each model varies the saturation and seismic intensity parameters to simulate structural behavior under critical combinations of loads. The results identify areas of potential local instability, providing a foundation for future strengthening measures.

Figure 18 presents the distribution of seepage flows within the dam body at PK 12+00. The vector field helps identify zones of increased water inflow and material migration, which can impact on the structural integrity and long-term reliability of the dam.

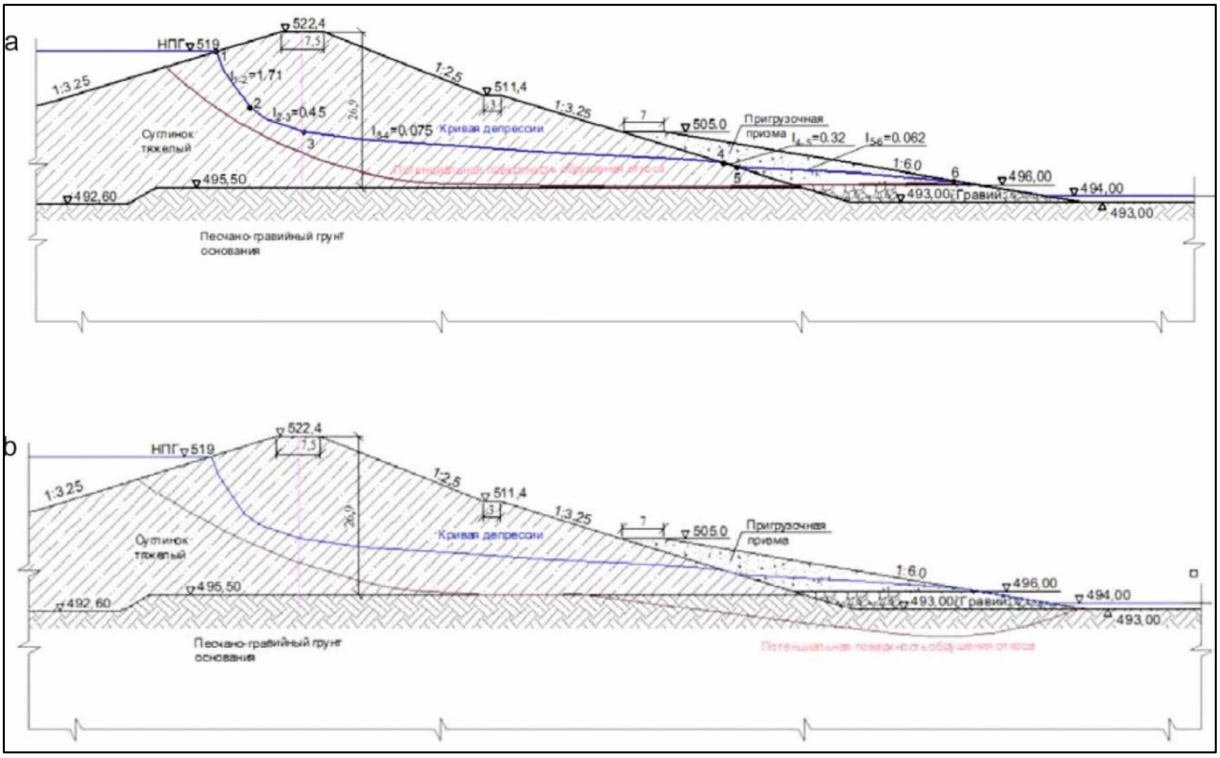

Figure 7 – Calculation Schemes:
a – PK 5+00, Load Case 1, Seismic Intensity – 7 points, Safety Factor (k) = 1.227;
b – PK 5+00, Load Case 2, Seismic Intensity – 8 points, Safety Factor (k) = 1.035

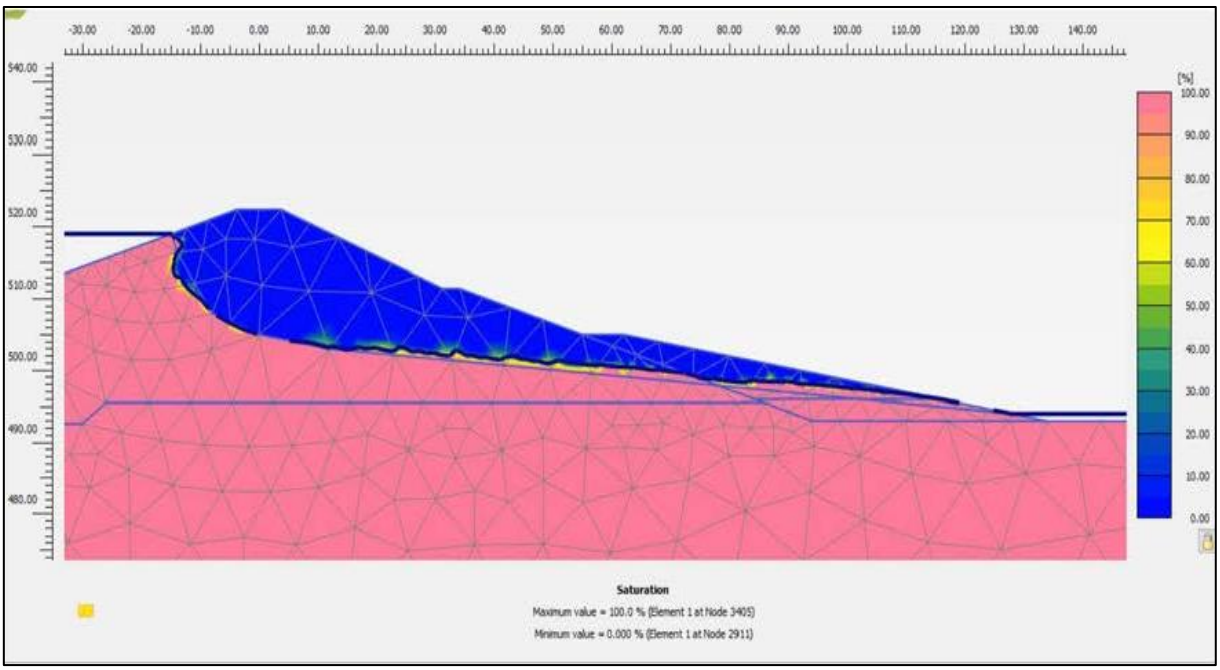

Figure 8 – Phreatic Surface at the Upstream Water Level of 519 m

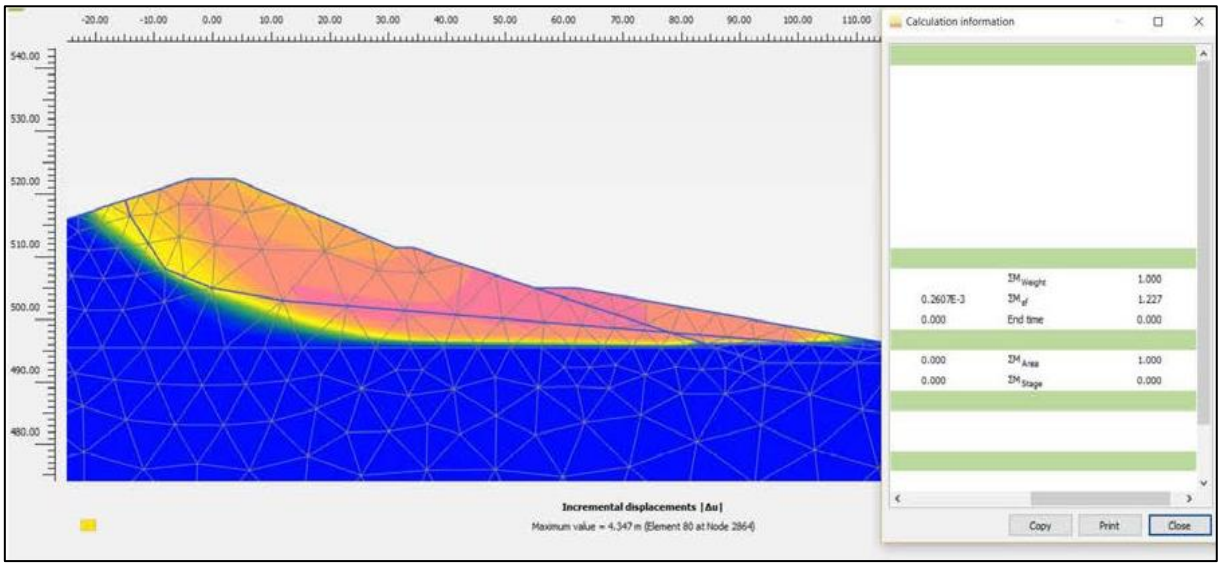

Figure 9 – Special Case 1: Potential Failure Surface of the Downstream Slope and Safety Factor

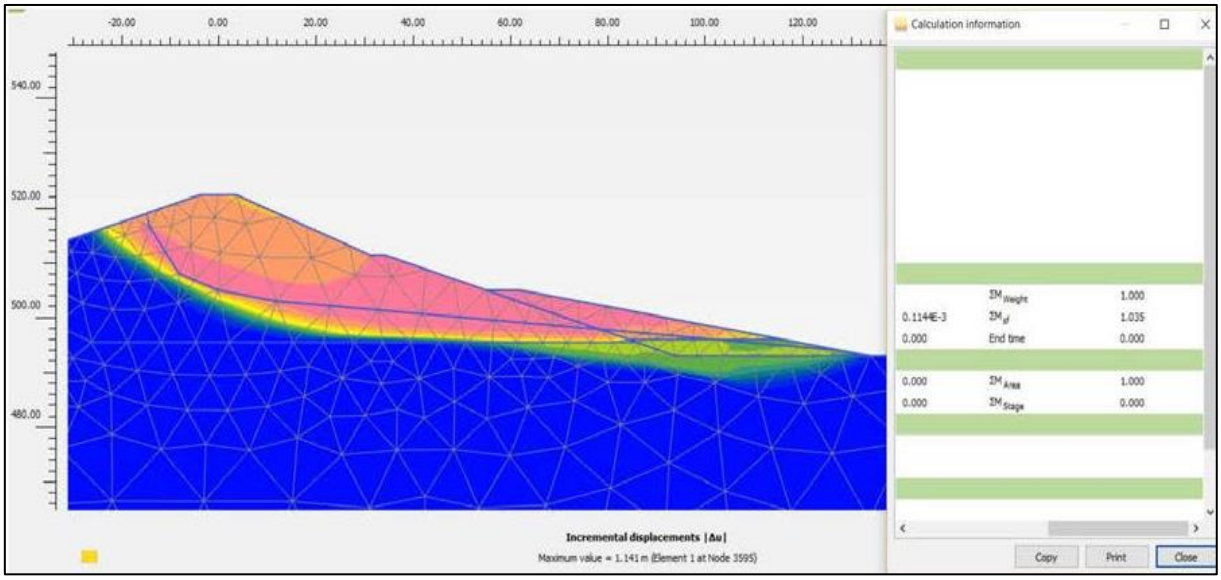

Figure 10 – Special Case 2: Potential Failure Surface of the Downstream Slope and Safety Factor

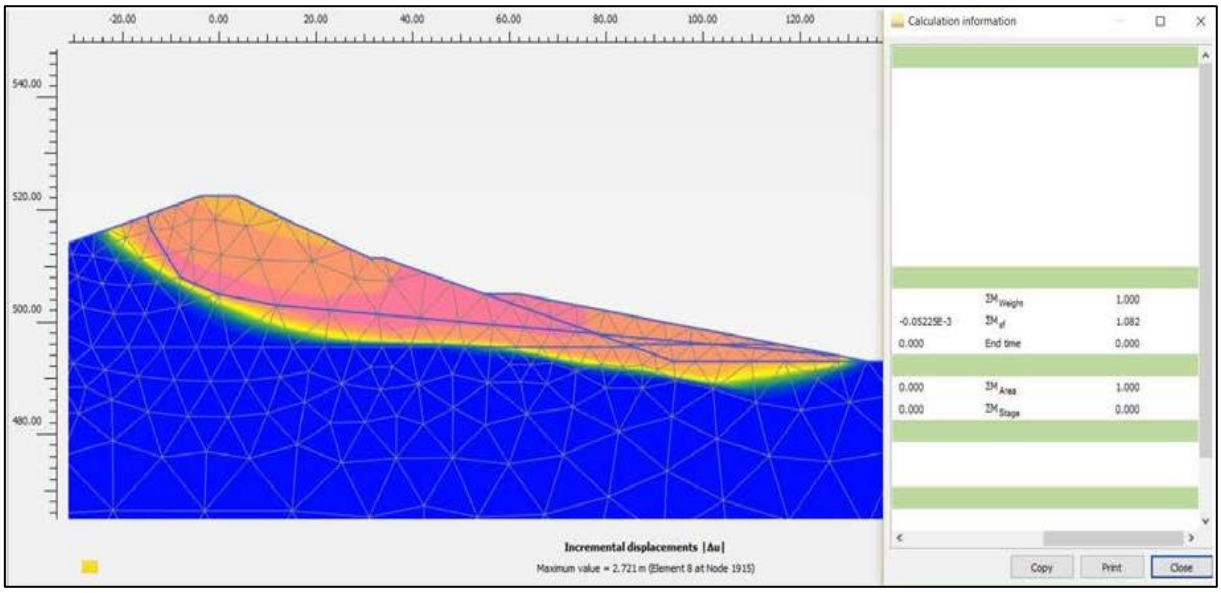

Figure 11 – Special Case 3: Potential Failure Surface of the Downstream Slope and Safety Factor

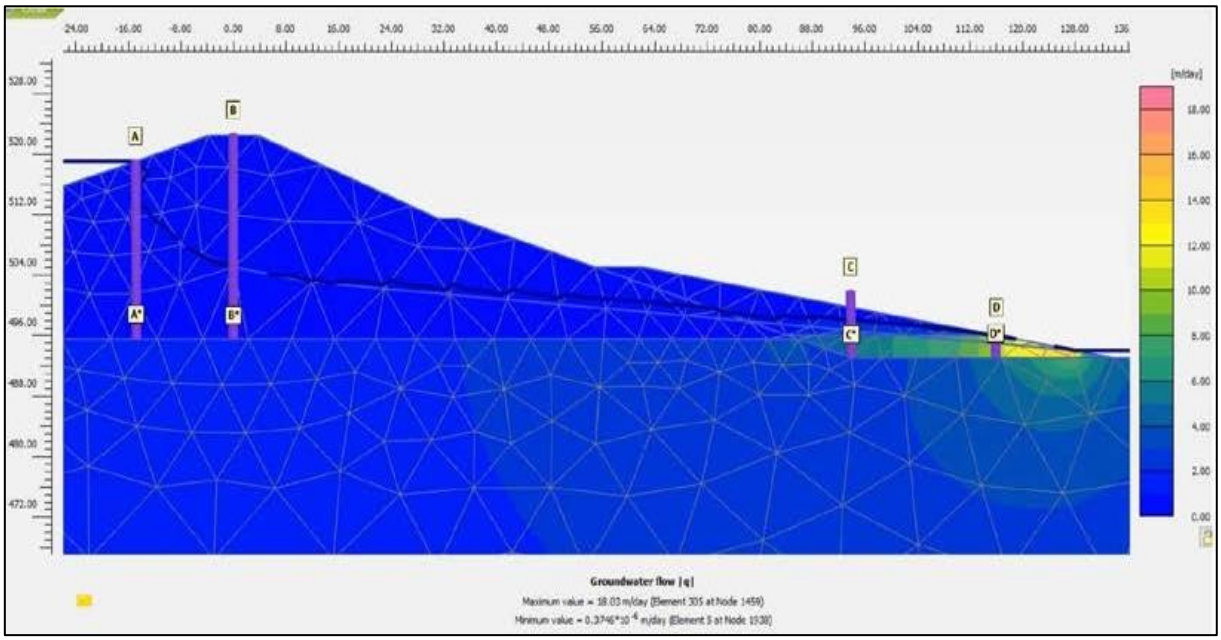

Figure 12 – Water Flow within the Dam Body at PK 05+00

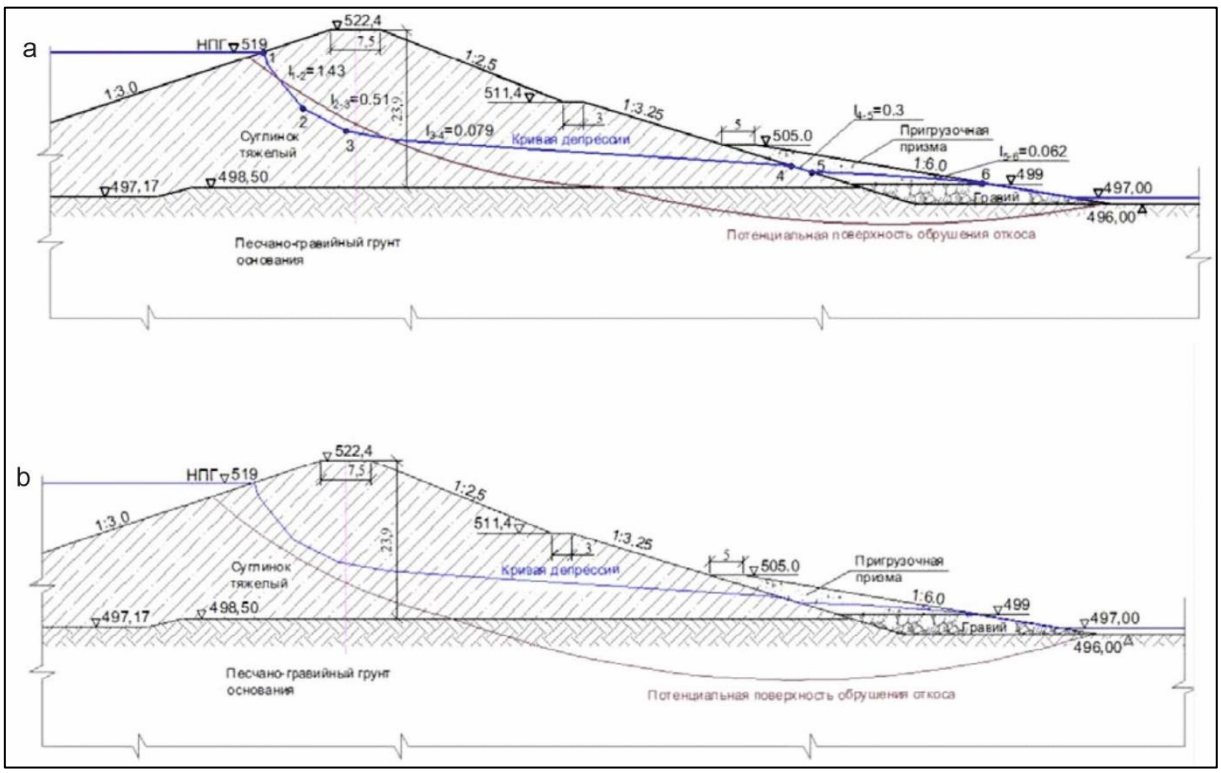

Figure 13 – Calculation Schemes:
a – PK 12+00, Load Case 1, Seismic Intensity – 7 points, Safety Factor (k) = 1.209;
b – PK 5+00, Load Case 2, Seismic Intensity – 8 points, Safety Factor (k) = 1.028

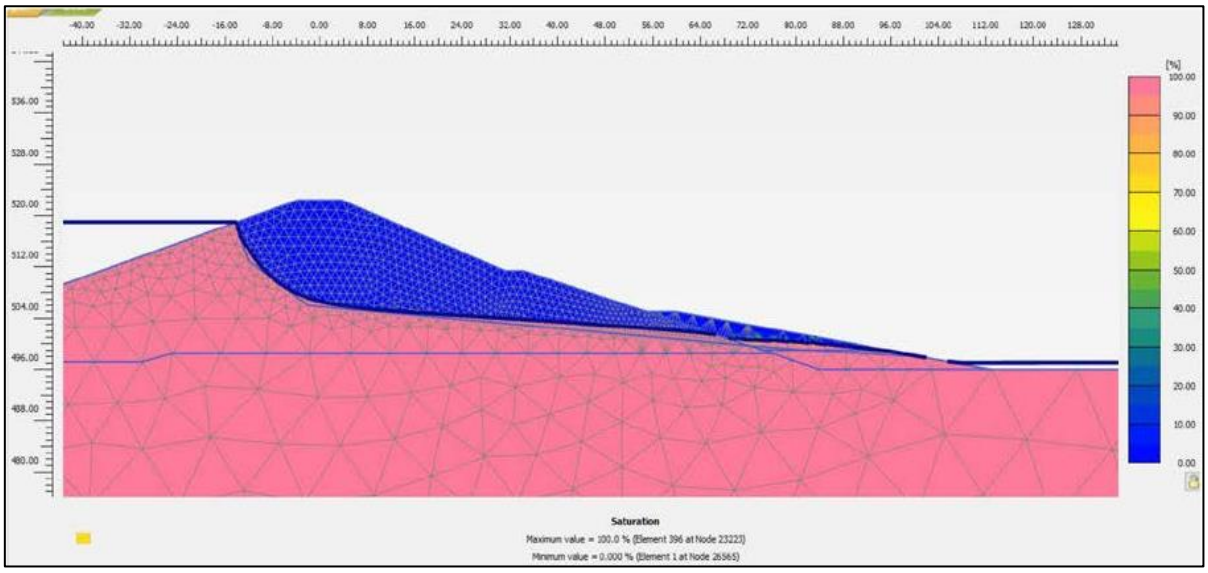

Figure 14 – Phreatic Surface at the Upstream Water Level of 519 m

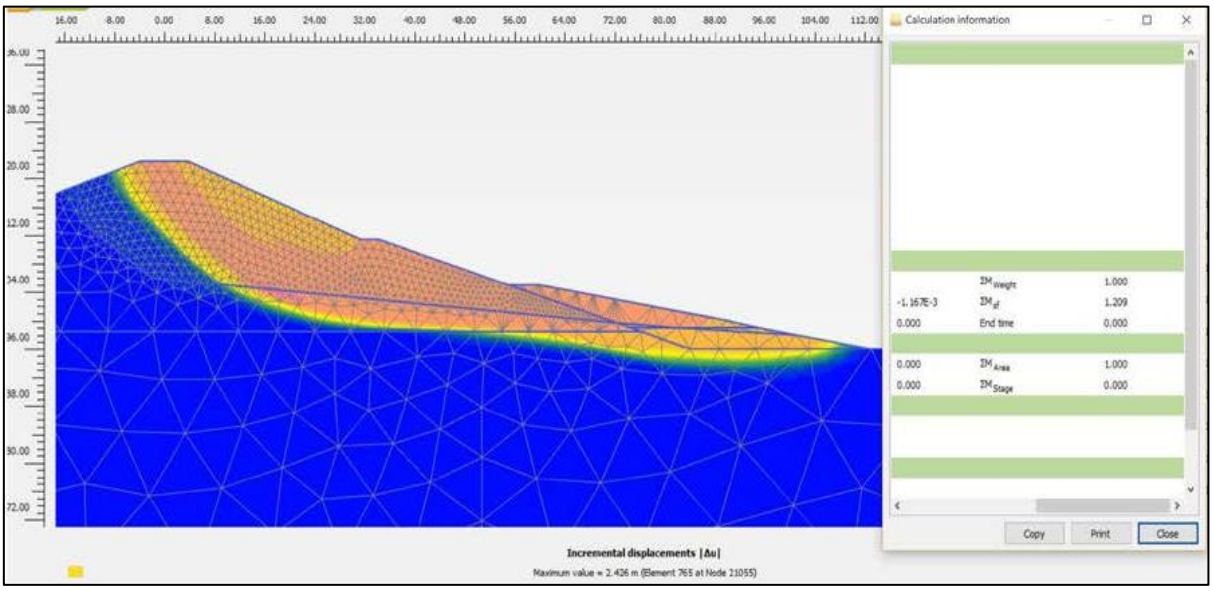

Figure 15 – Special Case 1: Potential Failure Surface of the Downstream Slope and Safety Factor

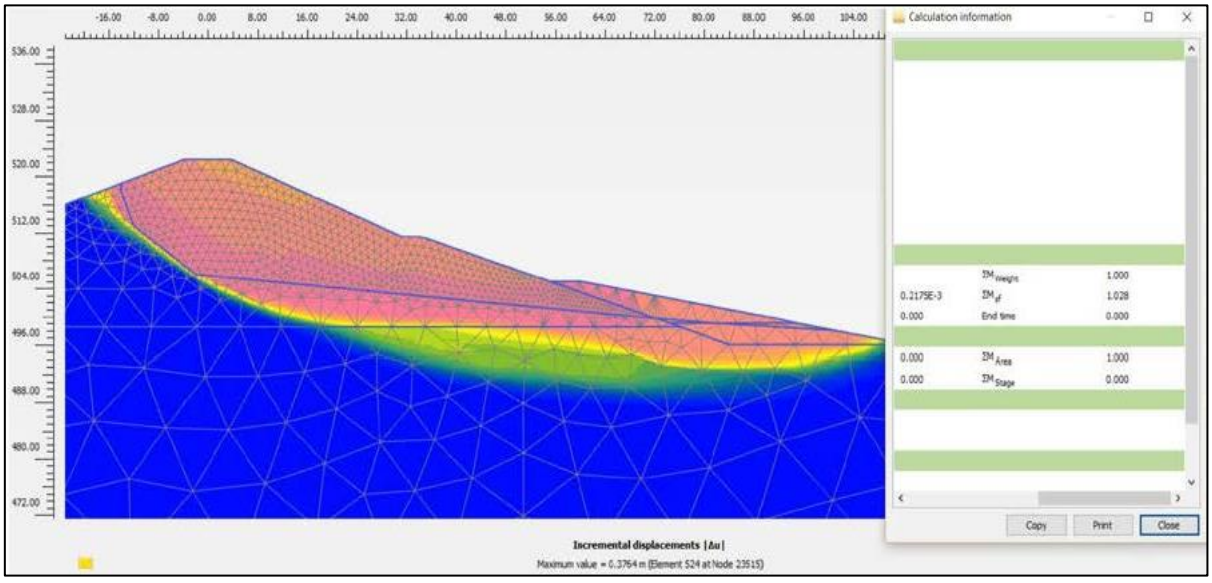

Figure 16 – Special Case 2: Potential Failure Surface of the Downstream Slope and Safety Factor

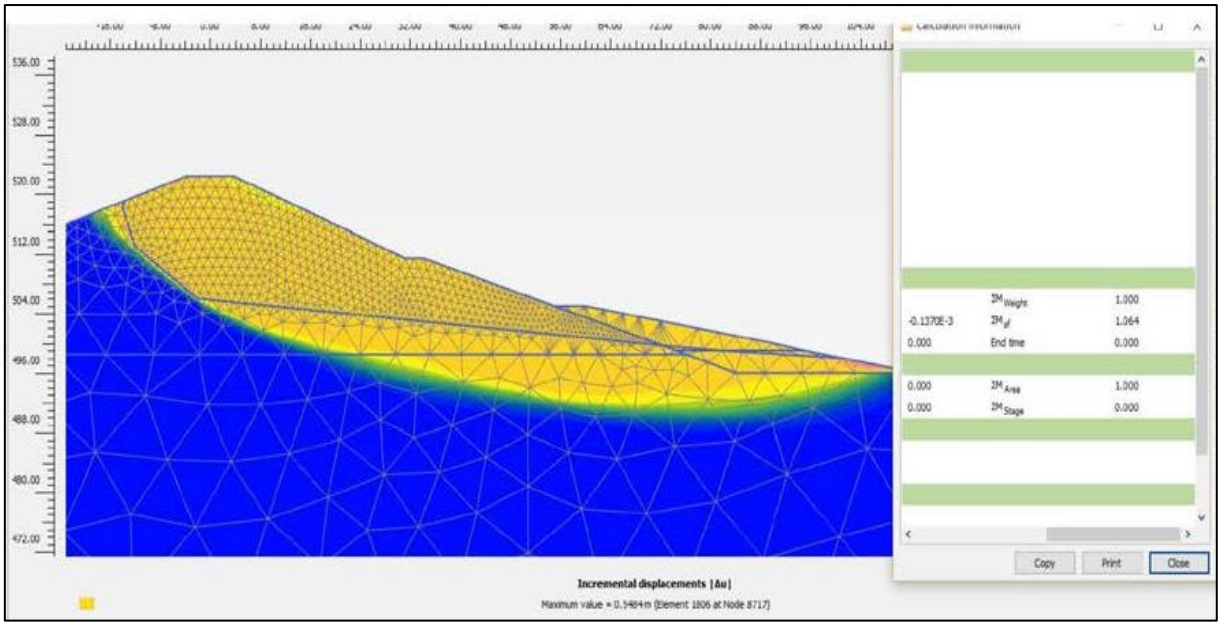

Figure 17 – Special Case 3: Potential Failure Surface of the Downstream Slope and Safety Factor

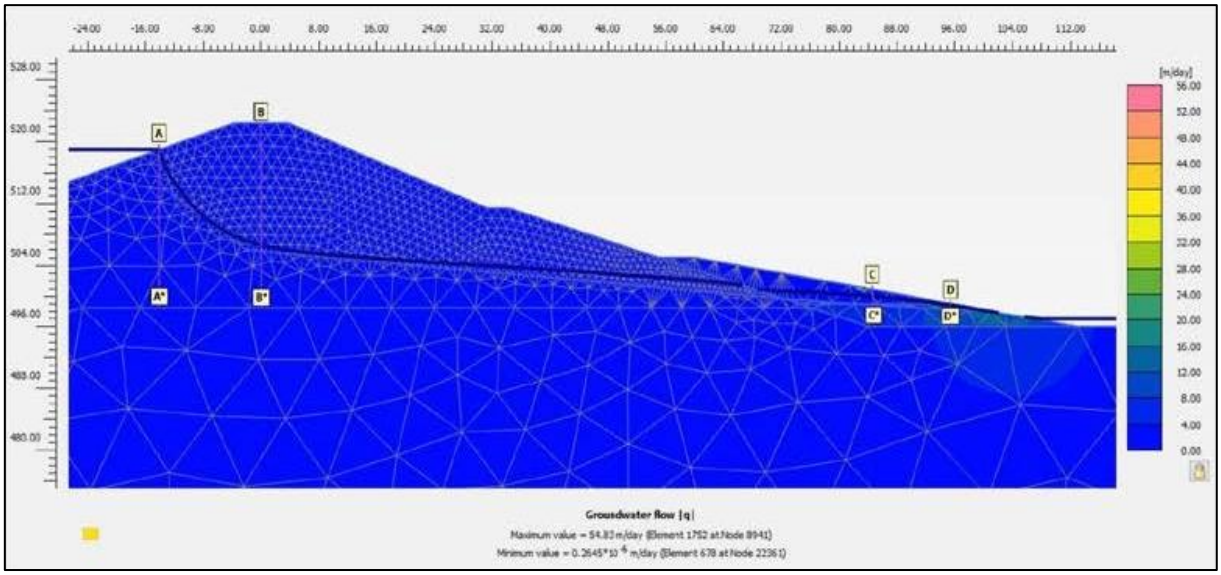

Figure 18 – Water Flow within the Dam Body at PK 12+00

The presented calculation results represent the initial iteration of numerical modeling. At this stage, preliminary data from engineering and geological investigations and field inspection parameters were used.

Further modeling and analysis will be refined and expanded based on the results of laboratory experimental studies, including tests for strength, permeability, and the deformation characteristics of soils and concrete. This will enhance the accuracy of computational models, enable calibration of input parameters, and provide a more reliable assessment of dam stability under various operational and seismic conditions.

The data obtained in subsequent stages will also serve as a basis for developing recommendations for seismic strengthening, monitoring, and planning of reconstruction measures.

5 CONCLUSIONS

1. A comprehensive multifactor assessment of the Tasotkel Dam, located in a seismically active zone of southern Kazakhstan, was conducted using modern methods for evaluating the technical condition of hydraulic structures. The assessment included visual inspection, instrumental and geodetic measurements, non-destructive testing, analysis of the physical and mechanical properties of soils, and inspection of reinforced concrete structures.

2. The inspection results revealed several defects and deviations from the design parameters, including localized damage to the upstream slope facing, signs of erosion, turf layer displacement, and discrepancies in the phreatic surface levels. Piezometric measurements confirmed the high drainage capacity of the foundation soils but also indicated the need for detailed monitoring of filtration processes.

3. Geodetic and instrumental observations did not identify critical deformations, though the analysis of archival data from 2010 to 2023 showed accumulated changes that require engineering intervention. The mechanical properties of soils mostly met regulatory standards, but certain zones with reduced strength were identified and required reinforcement.

4. Numerical modeling performed using the Plaxis 2D software allowed for an evaluation of slope stability under both static and seismic loading conditions (intensity of 7 and 8 on the MSK-64 scale). The calculations demonstrate satisfactory stability of the slopes after the proposed reconstruction measures. Visualization of filtration flows and potential failure surfaces identified critical zones and informed recommendations for their strengthening.

5. The study emphasizes the need to revise existing regulatory documents and standards governing the inspection of hydraulic structures. The analysis of previously conducted inspections revealed that they were largely superficial and fragmented, failing to meet modern safety and seismic resilience requirements.

6. The presented results represent an initial modeling iteration. Further laboratory testing is planned to refine input parameters and calibrate the models. This will improve the reliability of predictive assessments and support the development of reconstruction and seismic strengthening measures, as well as long-term monitoring programs.

7. The findings of this study confirm the importance of adopting a multifactorial approach to the diagnostics of hydraulic structures in seismically active regions. The methodology developed here can serve as a foundation for updating engineering safety guidelines and advancing national standards in the field of hydraulic infrastructure assessment.

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POROUS SiO_2-SiC BASED CERAMICS WITH LOW THERMAL CONDUCTIVITY

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Abstract. Porous SiO_2–SiC-based ceramics were developed to achieve superior thermal insulation and mechanical performance for high-temperature applications such as thermal protection and energy conversion systems. In this study, nano-sized SiO_2, nano-sized SiC, and carbon black powders were used to fabricate porous SiO_2–SiC ceramics by sintering in air at 700–1000 °C. The effects of nano-SiC content (0–35 wt%) and sintering temperature on porosity, thermal conductivity, and compressive strength were systematically investigated. Increasing the nano-SiC content and sintering temperature led to enhanced partial densification of the struts due to silica bonding, resulting in decreased porosity from 77.1% to 69.5%. The lowest thermal conductivity of 0.043 W/m·K was achieved for samples containing 10 wt% nano-SiC sintered at 700 °C, attributed to the high interfacial thermal resistance at SiO_2–SiC interfaces. The compressive strength of porous SiO_2-SiC based ceramics increased by 5.4 – 6.9 times with an increase in sintering temperature and the nano-SiC content from 0 to 35 wt% and remained significantly higher than that of previously reported porous SiC ceramics. The improved thermal insulation and mechanical strength were attributed to strong silica promoted interparticle bonding and the formation of SiO_2 core/SiC shell structures. These findings demonstrate that the newly developed porous SiO_2–SiC ceramics possess a promising combination of low thermal conductivity and high strength for advanced high-temperature applications.

Keywords: porous ceramic, SiO_2-SiC, porosity, thermal conductivity, compressive strength.

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ҒЫЛЫМИ МАҚАЛА

ТӨМЕН ЖЫЛУ ӨТКІЗГІШТІГІ БАР SiO_2-SiC НЕГІЗІНДЕГІ КЕУЕКТІ КЕРАМИКА

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Аңдатпа. Кеуекті SiO_2–SiC негізіндегі керамикалар жоғары температуралы қолданбаларда, мысалы, жылулық қорғаныс және энергия түрлендіру жүйелерінде жоғары жылу оқшаулау және механикалық қасиеттерге қол жеткізу үшін жасалды. Бұл зерттеуде ауада 700–1000 °C температурада күйдіру арқылы кеуекті SiO_2–SiC керамикасын алу үшін наноөлшемді SiO_2, наноөлшемді SiC және көміртек қара ұнтағы пайдаланылды. Нано-SiC мөлшерінің (0–35 масс.%) және күйдіру температурасының кеуектілікке, жылуөткізгіштікке және қысу беріктігіне әсері жүйелі түрде зерттелді. Нано-SiC мөлшерін және күйдіру температурасын арттыру кремнезем байланысының әсерінен қаңқаның жартылай тығыздалуын күшейтіп, кеуектіліктің 77.1%-дан 69.5%-ға дейін төмендеуіне әкелді. Ең төмен жылуөткізгіштік 0.043 Вт/м·К мәні 10 масс.% нано-SiC бар және 700 °C-та күйдірілген үлгі үшін анықталды, бұл SiO_2–SiC интерфейстеріндегі жоғары шекаралық жылу кедергісімен түсіндірілді. Кеуекті SiO_2–SiC негізіндегі керамикалардың қысу беріктігі күйдіру температурасы мен нано-SiC мөлшерін 0-ден 35 масс.% дейін арттырғанда 5.4–6.9 есеге өсті және бұрын хабарланған кеуекті SiC керамикаларына қарағанда әлдеқайда жоғары болды. Жақсартылған жылу оқшаулау және механикалық беріктік кремнеземнің бөлшектер арасындағы күшті байланысын және SiO_2 өзек/SiC қабық құрылымдарының түзілуін қамтамасыз етті. Бұл нәтижелер жаңадан әзірленген кеуекті SiO_2–SiC керамикаларының төмен жылуөткізгіштік пен жоғары беріктік комбинациясын иеленіп, жоғары температуралы заманауи қолданбалар үшін үлкен әлеуетке ие екенін көрсетеді.

Түйін сөздер: кеуекті керамика, SiO_2–SiC, кеуектілік, жылуөткізгіштік, қысу беріктігі.

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НАУЧНАЯ СТАТЬЯ

ПОРИСТАЯ КЕРАМИКА НА ОСНОВЕ SiO_2-SiC С НИЗКОЙ ТЕПЛОПРОВОДНОСТЬЮ

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Аннотация. Пористые керамики на основе SiO_2–SiC были разработаны для достижения превосходных теплоизоляционных и механических свойств при высокотемпературных применениях, таких как системы тепловой защиты и преобразования энергии. В данном исследовании для изготовления пористых керамик SiO_2–SiC использовались наноразмерные порошки SiO_2, SiC и сажи, которые спекались на воздухе при температуре 700–1000 °C. Влияние содержания нано-SiC (0–35 мас. %) и температуры спекания на пористость, теплопроводность и прочность при сжатии было изучено систематически. Повышение содержания нано-SiC и температуры спекания усиливало частичное уплотнение каркаса за счёт связывания кремнеземом, что приводило к уменьшению пористости с 77,1 % до 69,5 %. Наименьшая теплопроводность 0,043 Вт/м·К была достигнута для образцов, содержащих 10 мас. % нано-SiC, спечённых при 700 °C, что объясняется высокой межфазной тепловой сопротивляемостью на границах SiO_2–SiC. Прочность при сжатии пористых керамик на основе SiO_2–SiC увеличивалась в 5,4–6,9 раза с повышением температуры спекания и содержания нано-SiC от 0 до 35 мас. % и оставалась значительно выше, чем у ранее сообщённых пористых керамик SiC. Улучшенные теплоизоляционные и механические свойства объясняются прочным межчастичным связыванием, обусловленным кремнеземом, и формированием структур типа SiO_2-ядро/SiC-оболочка. Полученные результаты показывают, что новые пористые керамики SiO_2–SiC обладают перспективным сочетанием низкой теплопроводности и высокой прочности для передовых высокотемпературных применений.

Ключевые слова: пористая керамика, SiO_2–SiC, пористость, теплопроводность, прочность при сжатии.

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CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

АЛҒЫС / ҚАРЖЫЛАНДЫРУ КӨЗІ

Зерттеу Қазақстан Республикасы Ғылым және жоғары білім министрлігі Ғылым комитетінің ЖТН AP19174518 гранттық қаржыландыру шеңберінде жүргізілді.

МҮДДЕЛЕР ҚАҚТЫҒЫСЫ

Авторлар мүдделер қақтығысы жоқ деп мәлімдейді.

БЛАГОДАРНОСТИ/ИСТОЧНИК ФИНАНСИРОВАНИЯ

Исследование проводилось в рамках грантового финансирования Комитета науки Министерства науки и высшего образования Республики Казахстан ИРН AP19174518.

КОНФЛИКТ ИНТЕРЕСОВ

Авторы заявляют, что конфликта интересов нет.

1 INTRODUCTION

Advanced materials used in thermal protection systems, energy conversion systems, and high-temperature industrial installations must have properties such as extremely low thermal conductivity and structural stability at high temperatures. In thermal protection systems (e.g., in aviation, spacecraft, furnaces, and turbines), the primary role of the material is to suppress heat transfer from the high-temperature environment (flame, plasma, or hot gases) to the protected structures or equipment. The use of a material with high thermal conductivity in thermal protection systems is unacceptable, as heat can easily pass through it, which may lead to overheating of the internal parts of the structure and, consequently, to its failure. Minimizing heat losses is critical in energy conversion systems (such as gas turbines and thermoelectric generators). Materials with intrinsically low thermal conductivity maintain a stable thermal gradient (temperature difference), thereby enabling more efficient energy conversion. In high-temperature industrial facilities, heating conditions are often non-uniform. Materials with low thermal conductivity help localize heat within the desired zone, mitigating thermal stress and reducing the risk of structural failure. In aerospace applications, even a temperature rise of several hundred degrees can have catastrophic consequences. Therefore, materials must not only withstand extreme temperatures but also provide effective thermal insulation for internal components.

Porous SiC-SiO_2 ceramics possess unique properties such as chemical stability, excellent oxidation resistance, and mechanical integrity (**Sheng et al., 2019; Chen & Miyamoto, 2014**) [25,31]. Owing to their properties porous SiC-SiO_2 ceramics used for various applications such as catalyst supports (**She et al.,2003; Chun & Kim, 2005**) [28,27], membranes (**Sheng et al., 2019**) [25], hot-gas filters (Dey et al., 2011) [26], electromagnetic radiation absorbers (**Yuan, Cheng and Zhang, 2016**) [29], and microwave absorbers (**Yuan et al., 2016**) [30]. The incorporation of SiC into SiO_2 or SiO_2 into SiC creates more interfaces between the two phases, resulting in enhanced phonon scattering. Thus, porous SiO_2-SiC based ceramics have high potential for thermal insulation applications.

2 LITERATURE REVIEW

Thermal conductivities of porous SiC-based ceramics have been studied widely by many researchers which elaborated several methods to lower thermal conductivity of porous SiC-based ceramics: (1) porosity maximization by gel-freezing **(Yoon et al., 2007; Fukushima et al., 2010; Fukushima et al., 2014)**, direct foaming (**Kim et al., 2005; Jana et al., 2017**) [11,12], filament printing and partial sintering (**Gomez-Gomez et al., 2019**), sol gel process followed by supercritical drying (**Kong et al., 2014; Su et al., 2018**), compression molding (**Manoj Kumar et al., 2011**), chemical vapor infiltration and reaction (**Streitwieser et al., 2005**); (2) incorporating an in-situ synthesized thermally insulating secondary phase into porous SiC ceramics by partial oxidation of nano-sized SiC particles (**Malik et al., 2020**); (3) fabrication of nano-structures with nano-porosity or hierarchical porosity (**Wan et al., 2018**). Recently, **Jana et al., 2017** investigated the effects of direct foaming of SiC slurries followed by gel casting and

sintering on the thermal and mechanical properties of SiC foams and reported that the thermal conductivity and compressive strength were 4.3 W/mK and 1.7 MPa, respectively, at a porosity of 89%. Extremely low thermal conductivity of 0.026 W/mK showed SiC nanowire aerogels which have been processed by sol-gel process and subsequent supercritical drying at a porosity of 99,8 % (**Su et al., 2018**). SiC foam fabricated by gel-freezing method exhibited the thermal conductivity of 0.054 W/mK at 98% porosity (**Fukushima & Yoshizawa, 2014**). Introduction of polysiloxane derived silica into nano-SiC ceramics decreased the thermal conductivity to 0.047 W/mK and showed minimal loss of compressive strength of 1.8 MPa at a porosity of 72.4% (**Malik et al., 2020**). **Kim et al., 2020** studied the thermal and mechanical properties of silica-bonded porous nano-SiC ceramics and reported that the thermal conductivity and compressive strength were 0.057 and 2.5 MPa, respectively, at 70.2% porosity.

In this study several strategies were established to obtain very low thermal conductivity and maximized mechanical strength in porous SiO_2-SiC ceramics, compared to the previous studies: (1) addition of nano-SiC into nano-SiO_2 to create SiO_2-SiC interfaces, (2) addition of nano-sized carbon template into nano-SiO_2 powder to create pores, (3) sintering at the different temperatures from 700°C to 1000°C.

The effect of nano-SiC content and sintering temperatures on the porosity, microstructure, thermal conductivity, and compressive strength of the newly developed porous SiO_2-SiC ceramics were investigated.

3 METHODS AND MATERIALS

Porous SiO_2-SiC based ceramics were prepared using commercially available nano-sized SiO_2 (~25 nm, Aerosil 300, Degussa AG, Hanau-Wolfgang, Germany), nano-sized β-SiC (~50 nm, 97.5%, N&A Materials, Inc., USA), and nano-sized carbon black (~75 nm, N774, OCI Company, Ltd., Korea) as a sintering materials. Nano-sized SiO_2 powder (Slurry 1), β-SiC powder (Slurry 2), and carbon black (Slurry 3) were each dispersed in distilled (DI) water using SiC balls. Slurry 1 was prepared by conventional ball milling for 24 h, while Slurries 2 and 3 were processed by planetary ball milling for 2 h. Subsequently, all three slurries were combined and mixed using conventional ball milling for an additional 2 h. The resulting mixture was dried and then milled again with organic binders in ethanol for 2 hours, using SiC balls and a polypropylene jar. Four different batches were prepared by varying the β-SiC content from 0 to 35 wt%: S0, S10, S20, and S35, where the number indicates the wt% of β-SiC. The carbon content was kept constant at 40 wt%. Afterwards, the mixtures were dried overnight in an oven at 70 °C. The dried powders were then ground and granulated by passing through a 120-mesh sieve. The resulting powders were uniaxially pressed under 15 MPa into green compacts of two sizes: 7 × 7 × 14 mm^3 for compressive strength tests, and 10 × 10 × 2.5 mm^3 for thermal conductivity measurements. green compacts were sintered in air at 700–1000 °C for 2 h.

The sintered specimens were designated as follows: for example, S0-7, S10-7, S20-7, and S35-7, where the number after the dash (7) indicates the sintering temperature of 700 °C. A similar notation was used for samples sintered at 800 °C, 900 °C, and 1000 °C.

The theoretical density of the porous SiO_2-SiC ceramics was calculated using the rule of mixtures according to the following formula:

$$\rho_{th} = \rho_{SiO_2} V_{SiO_2} + \rho_{SiC} V_{SiC} \quad (1)$$

where, ρ_{SiO_2} and ρ_{SiC} are the theoretical densities of silica 2.196 (gcm^{-3}) and SiC (3.216 gcm^{-3}), respectively. V_{SiO_2} and V_{SiC} denotes the volume fraction of silica and SiC which calculated from change of the weight after sintering in air, respectively. The SiO_2 content calculated from the weight change after sintering by the following reaction:

$$SiC + O_2 \rightarrow SiO_2 + CO_2 \quad (2)$$

$$C + O_2 \rightarrow CO_2 \quad (3)$$

The bulk density of the sintered samples was calculated from the weight to volume ratio. The porosity of the samples obtained by following equation:

$$P = 1 - \frac{\rho_b}{\rho_{th}} \times 100 \quad (4)$$

where, P and ρ_b are the porosity (%) and bulk density of the porous SiO_2-SiC ceramics, respectively.

Microstructural analysis was carried out using scanning electron microscopy (SEM, S4300, Hitachi Ltd., Hitachi, Japan). Compressive strength was evaluated using an Instron 3344 testing machine (Instron Inc., Norwood, MA, USA) at a constant crosshead speed of 0.5 mm/min. The compressive strength of porous SiO_2–SiC ceramics was tested six times for each sample type to ensure reproducibility. Thermal diffusivity and heat capacity were determined using the laser flash method (LFA 467; NETSCH GmbH, Selb, Germany), with a thin graphite coating applied to the sample surfaces prior to measurement. Each sample was tested three times in an argon atmosphere. Thermal conductivity was calculated using the following equation [100]:

$$\kappa = \alpha \rho C_p \quad (5)$$

where ρ, α, and C_p denotes the sintered density, thermal diffusivity, and heat capacity, respectively.

Table 1

Batch composition and sintering condition of SiO_2-SiC ceramics

Sample designation	Batch composition (wt%)			Sintering condition	Remark
	SiO_2	β-SiC	CB		
S0	60	-	40	700°C/2h/Air 800°C/2h/Air 900°C/2h/Air 1000°C/2h/Air	0wt% SiC
S10	54	6	40		10wt% SiC
S20	48	12	40		20wt% SiC
S35	39	21	40		35wt% SiC

4 RESULTS AND DISCUSSION

4.1 Porosity and microstructure

Figure 1 shows the porosity of porous SiO_2–SiC-based ceramics as a function of the initial nano-SiC content, sintered at 700 °C–1000 °C in air. As the nano-SiC content increased from 0 wt% to 35 wt%, the porosity gradually decreased from 77.1% to 75.0% for samples sintered at 700 °C, from 76.9% to 74.3% at 800 °C, and from 75.4% to 72.2% at 900 °C. However, at 1000 °C, the porosity initially increased from 67.3% to 70.7% as the nano-SiC content increased from 0 wt% to 10 wt%, and then gradually decreased to 70.6% and 69.5% with further increases to 20 wt% and 35 wt%, respectively. The addition of nano-SiC further increased the density due to partial densification promoted by silica. The higher silica content enhances interparticle bonding, pulling adjacent particles closer together and resulting in partial densification.

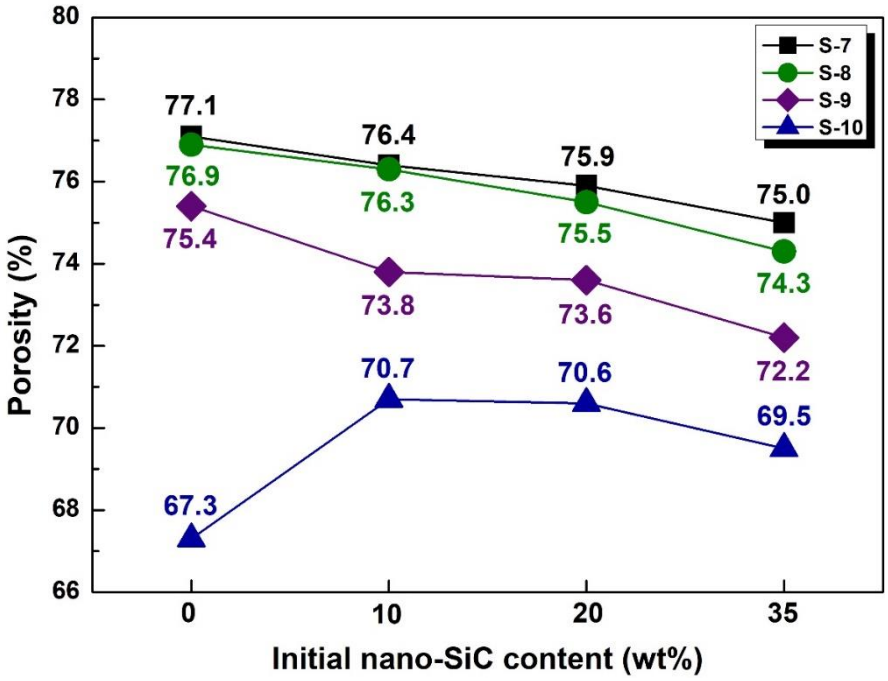

Figure 1 – Porosity of porous SiO_2-SiC based ceramics

The S0 samples exhibited a decrease in porosity from 77.1% to 67.3% when the sintering temperature increased from 700 °C to 1000 °C, respectively. This is attributed to increased partial densification due to increased silica content at high temperatures. The increased silica content causes strong inter-particle bonding, thus pulling the adjacent particles closer and causes partial densification. The increased silica content gives rise to strong inter-particle bonding, pulling adjacent particles closer to each other, and leads to the enhanced densification of the porous ceramics by viscous flow. The S10, S20, and S35 samples also exhibited a decrease in porosity from 76.4% to 70.7%, from 75.9% to 70.6%, and from 75.0% to 69.5% when the sintering temperature increased from 700 °C to 1000 °C, respectively.

Figure 2 shows typical microstructure of porous SiO_2-SiC ceramics sintered at 700 °C for 2 h in air. The SEM micrographs confirm a decrease in porosity with increasing nano-SiC content from 0 wt% to 35 wt% at a given sintering temperature. The microstructure exhibits small clusters of particle aggregates bonded together and two types of pores: inter-aggregate pores and intra-aggregate pores.

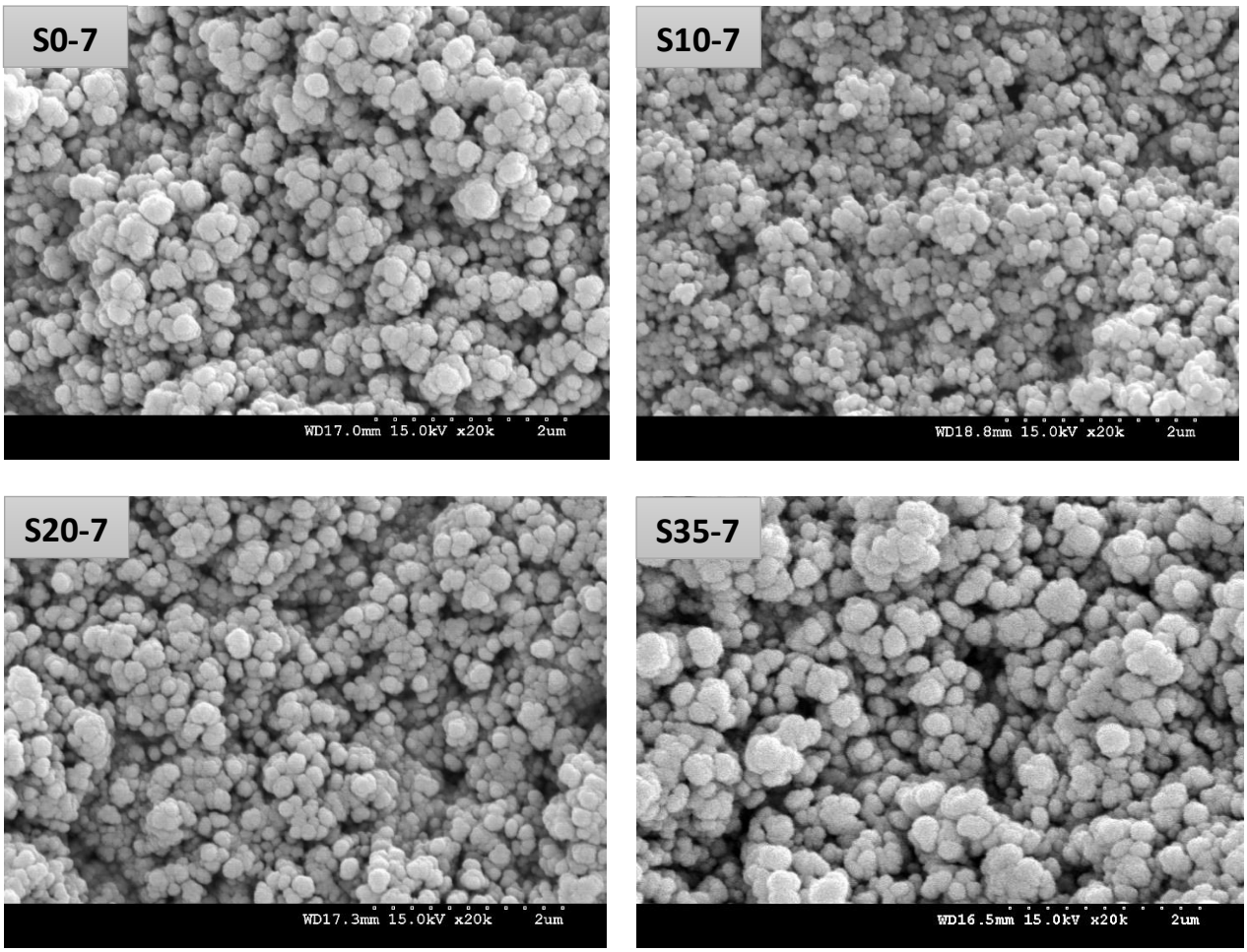

Figure 2 – The typical microstructure of porous SiO_2-SiC ceramics sintered at 700 °C for 2 h in air.

4.2 Thermal conductivity

Figure 3 exhibited the thermal conductivities of porous SiO_2-SiC based ceramics. The lowest thermal conductivity was achieved for sample S0-7 (porous SiO_2-SiC based ceramics with 0 wt% of nano-SiC content sintered at 700 °C). The thermal conductivity increased from 0.036 to 0.050 W/mK, 0.045 to 0.056 W/mK, and 0.050 to 0.059 W/mK with increasing the initial nano-SiC powder content from 0 to 35 wt% for S-7, S-8, and S-9 samples, respectively. However, the thermal conductivity of S-10 sample decreased from 0.127 to 0.076 W/mK when initial nano-SiC content increased from 0 to 20 wt%, respectively. Thermal conductivity of S10 (porous SiO_2-SiC based ceramic with 10 wt% of nano-SiC) sample increased from 0.043 to 0.087 W/mK with an

increase of sintering temperature from 700 °C to 1000 °C, respectively. Generally, thermal conductivity increases with decreasing porosity, and the porous SiO_2-SiC based ceramics sintered at 700 °C, 800 °C, and 900 °C followed this trend.

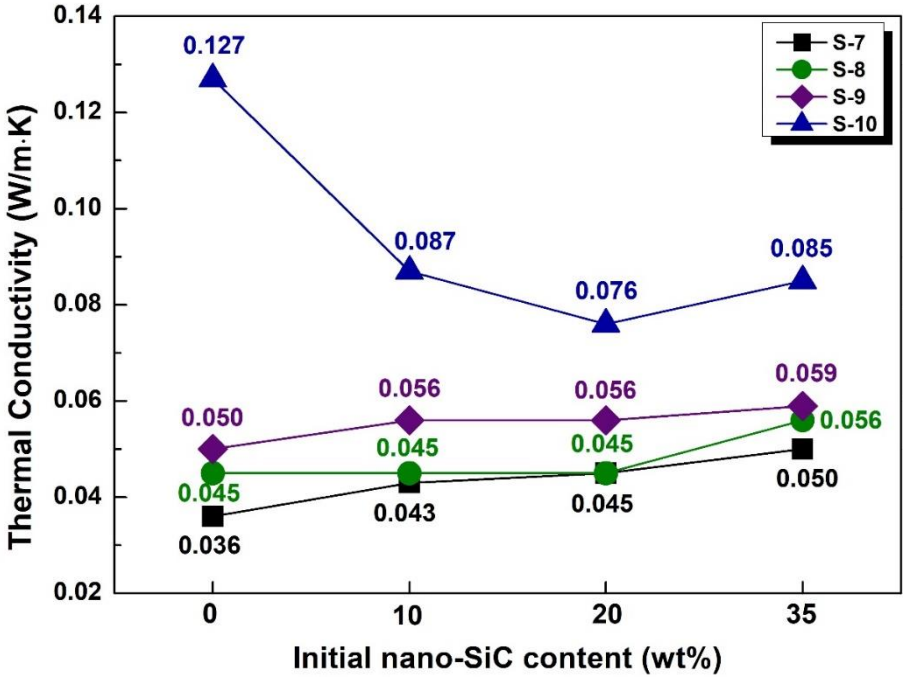

Figure 3 – Thermal conductivity of porous SiO_2-SiC based ceramics

These results suggest that the addition of nano-SiC into nano-SiO_2 increases thermal conductivity. The increase of thermal conductivity was attributed to the decrease of porosity. The porosity decreased with increasing the initial nano-SiC content was due to the partial densification of the porous SiO_2-SiC based ceramics by viscous flow and/or higher packing density of the green body.

Thermal conductivities of newly developed porous SiO_2-SiC ceramics were 0.045 W/mK (S10-8) and 0.043 W/mK (S10-7) which are one order of magnitude lower than that of porous nano-SiC ceramics 0.14 W/mK at the similar porosity of ~76.3% (**Wan & Wang, 2018**). The thermal conductivity of porous SiO_2-SiC ceramic with 20 wt% of nano-SiC sintered at 900 °C (S20-9) was lower (0.056 W/mK) than that the reported literature data (0.068 W/mK) at the similar porosity of 73.5% (**Wan, Gao and Wang, 2017**).

These results suggest that the addition of nano-SiC content into nano-SiO_2 could decrease the thermal conductivity of the porous SiO_2-SiC ceramic which was attributed to the increase of interfacial thermal resistance at the SiO_2-SiC interfaces.

4.3 Compressive strength

Compressive strength of porous SiO_2-SiC based ceramics is shown in **Figure 4**. The compressive strength of porous SiO_2-SiC based ceramics increased with increasing sintering

temperature. For example, the thermal conductivity of S0, S10, S20, and S35 increased from 3.0 to 20.7 MPa, from 2.9 to 15.7 MPa, from 2.5 to 10.9 MPa, and from1.9 to 6.9 MPa with increasing temperature from 700 °C to 1000 °C, respectively. The compressive strength of porous SiO_2-SiC based ceramics decreased from 20.7 to 6.9 MPa, 9.3 to 3.4 MPa, 4.3 to 2.9 MPa, and 3.0 to 1.9 MPa with increasing initial nano-SiC content from 0 wt% to 35 wt% for S-10, S-9, S-8, and S-7 samples, respectively.

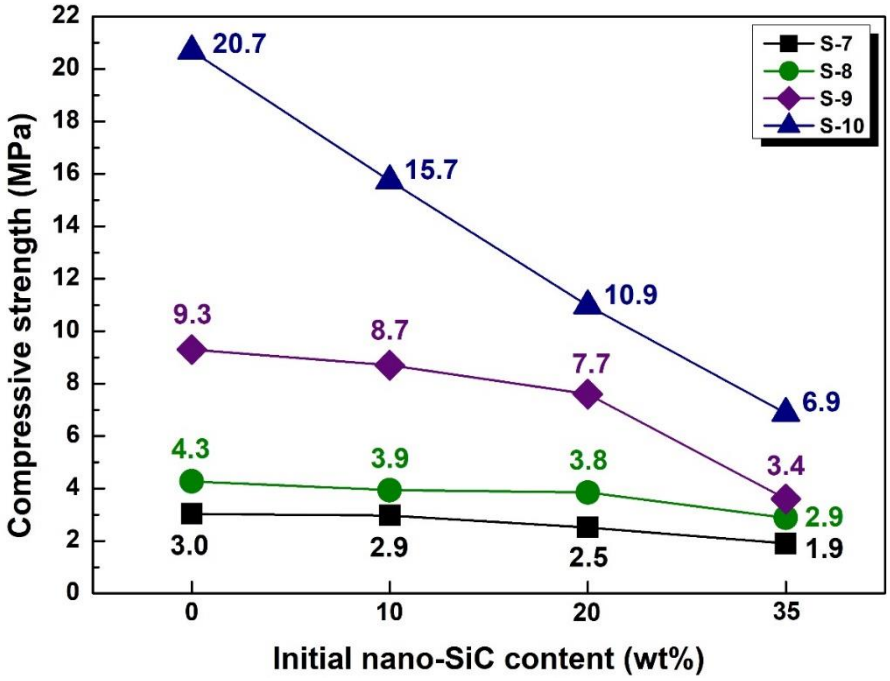

Figure 4 – Compressive strength of porous SiO_2-SiC based ceramics as a function of initial nano-SiC content

The compressive strengths of porous SiO_2-SiC based ceramics were 2 and 2,4 times higher (2.9 MPa for S10-7 and 3.9 MPa for S10-6, respectively) than that of porous nano-SiC ceramics (1.6 MPa) at a same porosity of 76.3% (**Wan & Wang, 2018**). The S20-10 sample exhibited the compressive strength of 10.9 MPa which was 4 times higher than that of porous nano-SiC ceramic reported in the literature data at the porosity of ~70.4% (**Kim et al., 2020**). Additionally, S35-9 sample (porous SiO_2-SiC based ceramic sintered with 35 wt% of nano-SiC at 900°C) showed the compressive strength of 3.4 MPa which is approximately 2 times higher than the literature data (1.8 MPa) at porosity of ~72.3% (**Malik et al., 2020**).

The present results suggest that the porous SiO_2-SiC based ceramics (S) with very low thermal conductivities of 0,043 – 0,056 W/mK exhibited much higher compressive strengths of 2,9 – 3,9 MPa than the previously reported SiC based porous ceramics. The highest strength and lower thermal conductivity of newly developed porous SiO_2-SiC based ceramics was attributed to the high strength interparticle bonding ensured by silica bonding and high interfacial thermal resistance obtained by introducing SiO_2 core / SiC shell structure.

5 CONCLUSIONS

The effects of nano-SiC content and sintering temperature on the thermal conductivity and compressive strength of porous SiO_2-SiC ceramics were investigated. The important findings are summarized as follows:

(1) The decreased porosity of the porous SiO_2–SiC ceramics with increasing nano-SiC content and sintering temperature was attributed to the enhanced partial densification of the struts caused by the increased silica content.

(2) The addition of nano-SiC into a nano-SiO_2 and nano-sized carbon template mixture is beneficial for increasing the thermal resistance due to the generation of additional interfaces, resulting in an extremely low thermal conductivity in porous SiO_2-SiC based ceramics reaching as low as 0.043 W/mK at 76.4 % porosity.

(3) The compressive strength of porous SiO_2-SiC based ceramics increased by 5.4 – 6.9 times with an increase in the nano-SiC content from 0 to 35 wt% when sintered at 700–1000 °C.

(4) The typical thermal conductivity and compressive strength values of thr porous SiO_2-SiC ceramics at 0.043 W/mK and 2.9 MPa, respectively.

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