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АРХИТЕКТУРА

СТРОИТЕЛЬСТВО

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RESEARCH ARTICLE

THE BARBICAN ESTATE AS AN EXPERIMENT IN THE ORGANISATION OF THE LIVING ENVIRONMENT

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Abstract *The organization of a comfortable living environment within residential complexes is gaining increasing importance today for a variety of reasons. This makes it necessary to look back and examine more closely the characteristics of residential environments that have stood the test of time and remain relevant, using the Barbican housing complex in London as an example. Through the analysis, synthesis, and generalization of theoretical studies, online resources, and historical materials on the subject, as well as from an interdisciplinary perspective, this article identifies the specific features of how the residential environment is shaped. This involves not only architectural and design considerations however also the psychological aspects of human perception and the prerequisites for fostering community formation. A comfortable, humane residential environment in an urban housing complex is characterized by a diversity of architectural, spatial, and planning solutions, integrating natural elements and placing a strong emphasis on human sensory and perceptual experience.The article examines the methods and techniques used to create spaces for living and leisure at the Barbican complex, highlighting humanistic aspects of the residential environment, such as architectural and typological diversity, a comfortable scale, distinctiveness, identity, and a harmonious blend of old and new elements. The research findings may be applied in future projects when designing contemporary residential environments.*

Keywords: *residential complex, Barbican, brutalism, housing experiment, living environment.*

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БАРБИКАН ТҰРҒЫН ҮЙ КЕШЕНІ ТҰРҒЫН ҮЙ ОРТАСЫН ҰЙЫМДАСТЫРУ ТӘЖІРИБЕСІ РЕТІНДЕ

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Аңдатпа. *Қазіргі уақытта тұрғын үй кешендеріндегі жайлы өмір сүру ортасын ұйымдастыру әртүрлі себептерге байланысты барған сайын өзекті бола түсуде. Уақыт сынынан өткен және бүгінде өз маңыздылығын жоғалтпаған тұрғын ортаны қалыптастыру ерекшеліктерін тереңірек зерделеу мақсатында өткенге жүгіну маңызды болуда. Бұл тұрғыда Лондондағы Барбикан тұрғын үй кешені мысал ретінде қарастырылады. Зерттеу тақырыбы бойынша теориялық еңбектерді, онлайн дереккөздерді, тарихи материалдарды талдау, жинақтау және синтездеу нәтижесінде, сондай-ақ пәнаралық дискурс тұрғысынан тұрғын үй кешенінің тұрғын ортасын ұйымдастырудың ерекшеліктері айқындалады – архитектура мен дизайн тұрғысынан да, адам қабылдауы психологиясы мен қауымдастық қалыптастыру алғышарттары тұрғысынан да. Жайлы және гуманистік бағыттағы қалалық тұрғын үй кешенінің ортасы архитектуралық, кеңістіктік, жоспарлау шешімдерінің әртүрлілігімен, табиғи элементтердің енгізілуімен ерекшеленеді және ең бастысы – адамның сезімі мен қабылдауына бағдарланған. Мақалада Барбикан тұрғын үй кешенінің тұрғындары үшін өмір сүру мен демалыс кеңістіктерін қалыптастыру әдістері мен тәсілдері талданып, тұрғын ортаның гуманистік қырлары анықталады. Оларға архитектуралық және типологиялық алуандылық, ыңғайлы ауқым, кешеннің танымалдылығы мен бірегейлігі, сондай-ақ ескі мен жаңаның үйлесімді байланысы жатады. Зерттеу нәтижелері заманауи тұрғын үй кешендерінің тұрғын ортасын жобалау барысында пайдалануға ұсынылады.*

Түйінді сөздер: *тұрғын үй кешені, Барбикан, брутализм, тұрғын үй эксперименті, тұрғын орта.*

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НАУЧНАЯ СТАТЬЯ

ЖИЛОЙ КОМПЛЕКС БАРБИКАН КАК ЭКСПЕРИМЕНТ ОРГАНИЗАЦИИ ЖИЛОЙ СРЕДЫ

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Аннотация. *Организация комфортной жилой среды жилых комплексов в настоящее время приобретает в силу различных причин все большее значение. Становится важным обратиться назад с целью более детального рассмотрения особенностей формирования жилой среды жилища, которое прошло проверку временем и не утратило своей актуальности в настоящее время, на примере лондонского жилого комплекса Барбикан. На основе анализа, обобщения и синтеза теоретических работ, онлайн источников, исторических материалов по теме исследования и с позиций междисциплинарного дискурса выявляются особенности организации жилой среды жилого комплекса, как со стороны архитектуры и дизайна, так и с точки зрения психологии человеческого восприятия и предпосылок для формирования сообщества. Комфортная – гуманная жилая среда городского жилого комплекса обладает таким качеством как разнообразие архитектурных, пространственных, планировочных решений, с включением природных элементов и обязательно ориентирована на чувства и восприятие человека. В статье анализируются методы и приемы формирования пространств для жизни и отдыха жителей комплекса Барбикан, что позволило выделить гуманистические аспекты жилой среды, такие как архитектурное и типологическое разнообразие, комфортный масштаб, узнаваемость комплекса и его идентичность, а также гармоничное сочетание старого и нового. Полученные результаты исследования могут быть использованы в дальнейшем при проектировании жилой среды современных жилых комплексов.*

Ключевые слова: *жилой комплекс, Барбикан, брутализм, жилищный эксперимент, жилая среда.*

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БЛАГОДАРНОСТИ/ИСТОЧНИК ФИНАНСИРОВАНИЯ

Исследование проводилось с использованием частных источников финансирования.

КОНФЛИКТ ИНТЕРЕСОВ

Авторы заявляют, что конфликта интересов нет.

Авторы заявляют о том, что при подготовке статьи не использовались технологии генеративного искусственного интеллекта и технологии, основанные на искусственном интеллекте.

1 INTRODUCTION

The concept of the residential environment encompasses apartments, houses, residential complexes, and external spaces such as courtyards, streets, and squares - essentially, the places where the daily activities of residents unfold. The residential environment serves as a tangible reflection of a society's culture, structure, and relationships. When thoughtfully organised, it can shape behaviours and improve the quality of life, thereby fostering a desirable living environment that remains relevant for many years. The quality of the residential environment impacts not only the demand and competitiveness of housing, but also the health and cohesion of its residents.

The design of mass housing in the post-war period became a topic of political and cultural debate **(Mumford, 1992)**. Architects believed that acceptable living conditions could be provided for the masses primarily through large residential complexes **(Strigalev & Han-Magomedov, 1972)**. It was envisioned that such complexes would transcend the mere function of habitation, creating instead a comfortable living environment **(Smithson, 1955)**. A series of housing projects aimed to propose experimental alternatives to the principles of the Athens Charter, offering innovative solutions to urban challenges through residential organisation. Two parallel approaches can be identified in the organisation of residential environments: one sought to overcome architectural limitations imposed by industrial technologies and standardisation, while the other - a contextual approach - focused on integrating existing urban contexts and cultural traditions **(Shipicyna & Margushin, 2013)**.

Architects pursued humanistic goals, striving to create a new world free from overcrowding, epidemics, conflict, and inequality. They believed architecture could play a role in shaping a sense of community. Simplicity of form, honesty in materials, and the integration of spaces **(Crosby, 1955)**, became synonymous with democracy. The influence of architects and architectural design was seen as profound and far-reaching **(Ryabushin, 1983)**. Perhaps the most significant project in terms of creating a humane residential environment is London's Barbican Estate, built in the Brutalist style between 1965 and 1982.

This study aims to identify the distinctive characteristics of the Barbican Estate's residential environment, focusing on its spatial and architectural planning, typological diversity, and developed infrastructure – all factors that have contributed to its enduring comfort, relevance, and desirability. The findings are expected to inform more deliberate approaches to the design of contemporary housing, inspired by the ongoing success of the Barbican model.

2 LITERATURE REVIEW

The war-damaged housing, emergent crises, and pervasive poverty gave rise to numerous social challenges that needed to be addressed rapidly. Key trends focused on finding solutions that prioritized speed and cost-effectiveness, not only emphasizing production efficiency but also considering societal needs. Equally significant was the spatial organization of housing within the urban framework, which was driven by the goal of minimizing travel time, architects' visions of a comfortable living environment akin to traditional urban settings, and the imperative to resolve pressing urban problems while respecting both heritage and future development.

During this period, efforts were primarily directed towards creating a humane environment, one that embraced a wide range of material and spiritual dimensions - a crucial consideration for cities and individuals ravaged by war. Such endeavours served as a foundation for more liberal and socialist approaches **(Moravanszky, 2017)**. A humane environment was understood as one that offered psychologically and physiologically comfortable living conditions, shaped by internal social and cultural factors that redefined housing as an interconnected system. In this context, Borthwick G. **(Borthwick, 2011)**, highlighted the importance of thoughtful planning from the outset, emphasizing several key strategies essential for a residential complex's long-term success as a thriving community and desirable living space:

a) Sound planning – by taking into account development density, the diversity of buildings, and the arrangement of buildings and open spaces within a mixed-use development, can enhance the community's overall perception, foster a shared culture, and encourage shared consumption experiences.

b) the philosophy of urban design - the theory upon which decisions were based within the project framework - including those concerning pedestrian and vehicular movement, the diversity and quantity of open spaces, and landscape solutions.

c) the significance and high level of attention to architectural and design details in the organisation of public spaces.

d) a thorough consideration of socio-economic factors that contributed to the success of the project, including multifunctionality, mixed-use development, variation in building heights, the design of high-quality housing, local community management of the complex, and partial self-sustainability through the inclusion of specialised cultural facilities.

The Barbican residential complex is a significant landmark of its time and a response to the already established image of urbanized living **(Mukhamedzyanova, 2009)**. The studies of this unique complex in the heart of London, characterised by high population density and still relevant and beloved by its residents, have attracted the attention of architects and urban planners for over half a century **(Tostoes & Ferreira, 2018)**. The architectural rigor of the project, its multifunctional program, and scale make the Barbican a highly significant work in the evolution of post-war British architecture. Although the complex is grounded in leading architectural concepts based on rationalism, the organisation of its residential environment has become a subject of study for specialists from various fields. The findings from these studies can undoubtedly be applied to the design of residential environments in contemporary housing complexes.

In contemporary research, the interest in the Barbican complex as urban housing is quite diverse and is linked to the examination of:

- the history of the site, archaeology, and the underlying assumptions of its design **(Sandes, 2018; Dzhenkins, 2021)**;
- the selection of spatial and planning solutions, along with architectural features of modernism and brutalism **(Tostoes, Ferreira, 2021)**;
- placement, organisation, and operation: public spaces within the residential complex; and the integration of housing into the urban fabric **(Mukhamedzyanova, 2009)**;
- the identity and identification of residents with the residential environment of the complex, from the perspective of the relationship between the organization of the architectural space and the formation of the community **(Sandes, 2014; Semprebon, 2017)**, highlighting that not only do the residents strongly identify with the place, but also many of those who work there **(Biehl et al., 2014)**. Furthermore, from the perspective of the designed public open spaces, which shape open areas resembling London squares and create an atmosphere for residents reminiscent of the traditional old London architecture **(Dieffenbacher, 2018)**;
- methods for improving urban housing from the perspective of studying typologically diverse buildings on the site, with mixed-use development **(Chopalavov, 2003)**, and the organisation of multi-level pedestrian spaces within the residential environment of the complex **(Lisina, 2020)**.

Despite the diversity of theoretical studies, this article aims to explore the specific features of the formation of the residential environment within the complex and to identify the humanistic aspects, which, in our opinion, are reflected in the variety of approaches and methods used to create spaces for living and leisure.

3 MATERIALS AND METHODS

The research methodology is based on a comprehensive approach, involving the analysis, generalisation, and synthesis of literary, scientific publications, and online sources. The sources considered directly addressed the research topic as well as the interdisciplinary discourse aimed at defining the characteristics of the formation of the residential environment within the complex. The materials selected for citation were those that most fully aligned with the objectives of the article.

A significant contribution to the research was made by the photographic documentation and observations of Dr. Architecture A.T. Akhmedova, based on her personal observations during a visit to the Barbican complex.

The following tasks were set within the scope of the research:

- identifying the architects' intentions regarding the organisation of the site, based on the consideration of advanced ideas for residential environment formation in the 1950s-1960s;
- Identifying the characteristics (methods and techniques) of the residential environment organisation at the Barbican complex, which remain relevant today.

When considering the organization of the living environment from a humanitarian perspective, attention should be given to human activities and their spatial surroundings - the environment that determines the behaviour of the user, unconsciously producing and reinforcing the values accepted in society. In examining the qualities of the residential environment from the standpoint of traditional housing development **(Arakelyan, 2011)**, comprehensive land use based on theoretical methods of information study and systematisation **(Baluhina & Gibadulina, 2021)**, and empirical studies of the physical activity of residents **(Baluhina & Gibadulina, 2022)**, as well as research on the organisation of residential quarters in European countries through methods of comparison and generalisation, researchers identify the humane (qualitative, value-based) aspects. A key condition here is the interconnection and mutual influence between the architectural environment and the individual's awareness of their surroundings, i.e., the human factor – the "spiritual" (internal) factor, reflected through cognitive features, visual perception, and behaviour. Based on an interdisciplinary approach, Arakelyan R.G. **(Arakelyan, 2011)** identified key aspects of spatial behaviour, reflected in the psychological and visual perception of the traditional environment, characterised by typological and functional diversity, a well-developed infrastructure, the inclusion of natural elements, recognisability, and a comfortable scale, which the author refers to as "traditional historical values". In our view, these "values" are an important condition for creating a humane living environment. The starting point in forming a humane living environment, especially in the city, also includes the successful implementation of construction-technological **(Vologdina & Yarukov, 2018)** and socio-spatial characteristics, natural-landscape organisation of the territory, and the creation of spaces for intensive pedestrian activity, promoting walking and interaction among residents, following the important principle of "designing emotions" **(Dagdanova, 2014)**. Approaching a high level of the aforementioned characteristics determines the solution to the main task of a "humane" living environment, namely, the comfort of living and the social effectiveness of the designed object. Based on the qualitative characteristics of the living environment outlined above, the article discusses architectural techniques and methods reflected in the design of the "space of dialogue" in the development of the residential environment of the London Barbican complex.

4 RESULTS AND DISCUSSION

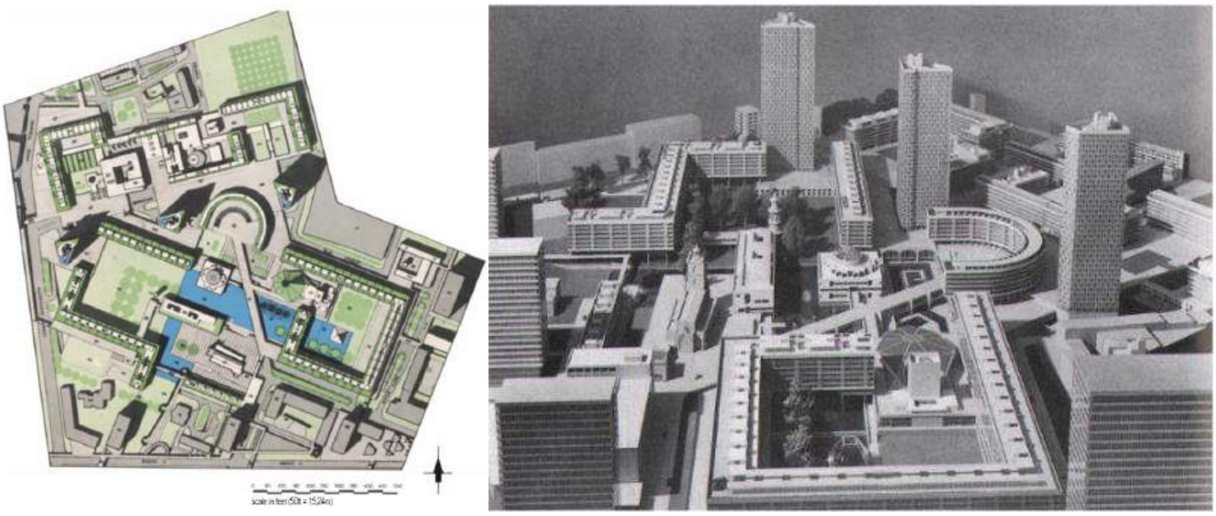
The area of London was severely damaged by bombing during the war, with many buildings being destroyed. The vacant land, strategically located in the heart of London (a 35-acre site), long known as the Barbican, was decided to be developed for mass housing. A competition was announced by the city authorities, with the winning project coming from the architectural firm Chamberlin, Powell & Bon. The architects – Peter Chamberlin, Geoffrey Powell, and Christoph Bon **(Hughes, 2022)** proposed creating a residential quarter on the site, a sort of architectural and social experiment, equipped with housing and all the necessary infrastructure, embodying the leading architectural ideas of their time. As advocates of modernist style, the architects used Brutalism as a symbol of London's revival after many years of horror and widespread destruction.

According to the master plan, the designated area accommodates residential buildings (in the form of three towers, each 42-44 stories high, thirteen seven-story residential buildings, and townhouses), educational and cultural facilities (a music and drama school, a girls' school, a cultural centre, a gallery, a library, a theatre, and a cinema), and recreational spaces (cafés, restaurants, a greenhouse, a private artificial pond with rest areas and fountains). The entire complex forms a cohesive ensemble **(Tsubaki, 2012)**, linked by air bridges, corridors, staircases, walkways, pedestrian paths, and landscaped and water features, creating a unified space—a living organism in the heart of the city **(Figure 1)**. Architects considered the combination of housing, leisure, education, and culture as key elements for the success of the project- both from a social and financial perspective. To achieve financial objectives, the concept of mixed-use development was employed, integrating various functions within the building.

It is no secret that as cities grow, their central areas gradually become emptied of residential neighbourhoods, increasingly giving way to public and commercial spaces **(Frearson, 2014)**. The Barbican, on the other hand, is one of the largest residential complexes in terms of land area. Its primary design concept focused on ensuring the maximum comfort for its residents and protecting them from the negative effects of the bustling city centre. According to experts, the Barbican is a unique project not only because of its scale and the infrastructure it provides, but primarily due to the reintegration of a large residential development into the city centre. "... In our scheme, the need to simultaneously meet three different requirements – high-density housing, schools, and large open spaces - was addressed by transforming the existing, decayed area into a large garden" **(Chamberlin, Powell & Bon, 1959)**, which is a rare occurrence in large cities like London.

Raising the complex above street level on stilts allowed for the separation of pedestrian and vehicular traffic, enhancing safety. Continuous ribbon windows ensured an influx of natural light—an important consideration in the frequently overcast British climate. The integration of natural elements such as water and greenery contributed to creating spaces with visual qualities reminiscent of traditional residential architecture.

In summary, the Barbican's distinctiveness lies in its successful balance of unity and variety. Unity is embodied in its coherent compositional vision and brutalist architectural language, while variety is reflected in the diverse array of living and recreational spaces. These spaces differ in design yet are equally functional, comfortable, and human-centred.



(a) (b)

Figure 1 – Master plan of the Barbican residential complex, 1959 (a); Model of the complex, 1959 (b) **(Chamberlin, Powell & Bon, 1959)**

The diversity of the housing complex is evident in several key organisational features:

- the building volumes were determined by the inclusion of high-rise residential towers, mid-rise apartment buildings, low-rise homes with individual entrances and plots, standalone public and educational buildings, as well as large recreational areas with their own distinct atmosphere. "The architectural scale evolves in three stages: from the modest and often intimate layer at the pedestrian level, through the larger scale of the upper layer of long terrace-balconies… to the powerful vertical dimension expressed by the towers. Everywhere, the main design goal was to create a sense of clarity without monotony" **(The Barbican Estate, 2021)** as noted by the project architects.

- in terms of spatial organisation, this involves a harmonious combination of greened and water-enriched spaces, transitional and intimate areas, residential and public spaces, where buildings are not perceived in isolation, but rather blend with the various levels of the landscape **(Smirnova, 2015)**. Furthermore, it is important to note the thoughtful separation of pedestrian and vehicular flows across different elevation levels. The residential complex is situated on a concrete platform raised 5-10 metres above the surrounding area **(Figure 2 (a))**, Vehicle movement occurs at ground level, while pedestrian walkways are positioned on the platform level, fully separated from traffic. Parking areas for cars and bicycles are also located at ground level.

Mobility played a crucial role in the development of the project. The highwalk pedestrian system is an integral part of the design. The concept of living just minutes away from work and amenities, which helps reduce overcrowding and, consequently, the daily stress of urban residents, was a key condition of the project. Some critics initially viewed the highwalk system as an unfortunate aspect of the design **(Benem, 1973)**. However, considering the architects' interest in creating a secluded oasis for its residents, the elevated walkways achieve exactly that – they establish a boundary around the complex, resembling a fortress:

- in the successful synthesis of open, semi-open, and closed spaces, a spatial and visual diversity is created, revealing new views and perspectives. Bradley S. and Pevsner N. described the landscape design of the Barbican as one created within the realm of the sublime and picturesque, evoking grandeur and awe in its aesthetic and spiritual components. This was reflected in the contrast between the tall towers and the horizontally stretched five-story residential blocks, as well as, for instance, in the bridge - a crossing over the lake, from where "one can admire the swirling waters of the cascades, as if from a bridge over a mountain gorge" **(Bradley & Pevsner, 1997)**;
- the combination of straight and curved lines in the spatial design, where the environment and form are created using primitive lines, with rounded forms providing not only structural integrity but also symbolising the completeness of form and line, both in the buildings and the landscape, thus creating a "pattern" in the facade designs;
- the volumetric-spatial dynamic contrast, where tower-type buildings, horizontally elongated six-storey houses, and townhouses are successfully positioned. To emphasise the strict orthogonal geometry of the towers and terraces, a semi-circular bend is highlighted in the floor plan, with vaulted canopies on the terraces, round forms in the landscape organisation, and water recreational elements such as fountains and waterfalls;
- the design of door and window openings, navigation systems (signs and markers), resting and leisure areas, down to the smallest details for the apartments, such as stylish modern door handles and light switches;
- methods and techniques in the organisation of water features: in one area, there is a lake with a waterfall, in another – calm water surfaces, and in a third – fountains. Meanwhile, the creation and integration of water elements and greenery into the living environment has contributed to the "softening" of the visual perception of the harsh concrete surfaces of the main buildings, where the contrast between the harsh architecture and nature creates a unique and distinctive atmosphere;
- the texture of the building surfaces. In concrete, as the main material for residential buildings of the 1960s, architects saw honesty towards the residents and an unhidden beauty. However, in the Barbican complex, the concrete surfaces were reinterpreted by the architects through the creation of various textures: smooth polished, rough, with the inclusion of stone chips, which give the surfaces visual diversity. To complement the concrete and balance its visual massiveness and monolithic appearance, dull red brick was chosen, reminiscent of the old warehouse buildings that once stood on the site. The colour of the red brick was selected for the public buildings, high-level walkways, and some podium buildings, reflecting the colour contrast, scale, and texture;
- the colour scheme: the monotonous concrete surfaces of the building contrast with the brick walls, the coloured coating of the pathways and playgrounds, and, of course, the greenery - lawns, shrubs, trees - which change colour depending on the season;
- the integration of a 16th-century church building and an old preserved section of the fortress wall into the modern construction **(Allan, 2021)**, representing the organic combination of the old and

new, tradition and modernity. References to the history of the place can also be traced in the naming of the residential blocks, named after prominent figures (e.g., the Defoe House, More House, Shakespeare House, etc.).

- in the layout of the apartments – from one-bedroom studios to three-storey penthouses and houses with adjacent plots - the design was developed to maximize natural light in all rooms. As such, bedrooms, dining rooms, and living rooms are positioned along the outer walls, while kitchens and bathrooms are placed along the inner walls. Meanwhile, the open spaces are designed to reflect the typical size familiar to Londoners – akin to the classic residential garden spaces of early London buildings - on a human scale. This design allows for the awareness of others using or living on the opposite side of the space, while still providing a comfortable level of privacy.

The arrangement and design of the apartments reflect a strong modernist influence: this is evident in the interior organisation, the careful attention to spatial proportions, and the "open" layouts with private balconies. Typically, an apartment would have only two doors - one to the bathroom and one to the entrance - leaving the remainder of the space configured to accommodate various functions and the diverse needs of residents.

The transformation potential of the living space was addressed through the use of sliding shutters, which expanded the room by integrating the balcony, visually merging it with the natural environment of the courtyard. This approach extended the concept of the home beyond the doorstep, transforming it into a beneficial surrounding environment - a personal habitat.

A synthesis of private living and urban life was achieved by creating spaces equally accessible and convenient for both local residents and city dwellers. For example, the Barbican Centre, located in the heart of the development, houses contemporary art galleries, performance halls, a public library, a winter garden, theatres, cinemas, and schools. These facilities attract people from across London, embodying the idea of blending private and public life. As Europe's largest multi-functional arts centre, the Barbican offers public spaces that serve various audiences - residents of the complex, local community members, and visitors from the wider city. These spaces can be indoors, outdoors, or sheltered, spanning levels from ground floor to the elevated podium. Furthermore, the spaces themselves vary in nature, from open public areas connected to the external city environment to more intimate semi-private gardens adjoining the residential blocks **(Figure 2(b))**. This variety of public spaces has been one of the key conditions fostering a sense of community.

(a)

(b)

Figure 2 – The Barbican residential complex: view from the bridge (a); the recreational area of the Barbican residential complex (b) (author's material)

The thoughtful design of public spaces, on the one hand, encourages interactions among residents, and on the other, supports visual oversight of the complex's territory. This balance between interaction and supervision has helped establish an active local community that maintains order, deliberates on the necessity and feasibility of modifications to the housing structure, organises events, and provides spaces for communal activities and hobbies (such as club rooms accessible to all residents). They also arrange children's playgrounds, strengthening social ties and passing on cultural values. In doing so, they bring to life the architects' aspiration to create an ideal way of living.

A socially diverse resident population was anticipated, with apartments of varying sizes and configurations placed in buildings of differing heights, offering choices based on financial means and/or desired level of comfort **(Barbican Londen, 2020)**. Regarding occupancy, the architects aimed from the outset to ensure a balanced composition of the projected permanent population, comprising families, couples, and single individuals. As a result, while preliminary research indicated the greatest potential demand would come from young urban professionals, only 4% of the 2,014 completed units are single-room apartments. The remaining distribution includes 40% three-room units, 26% two-room units, 22% four-room units, and 8% five-room units.

It is worth noting that the architects' approach to the design and spatial organisation of the residential complex was based not solely on housing as a material expression, but also took into account the visual and psychological aspects of human perception. This resulted in an integrated living environment that is equally comfortable for people of varying income levels, occupations, family structures, and ages. The complex today stands as evidence that, with well-considered residential planning, it is possible to create comfortable living conditions while simultaneously achieving high-density development.

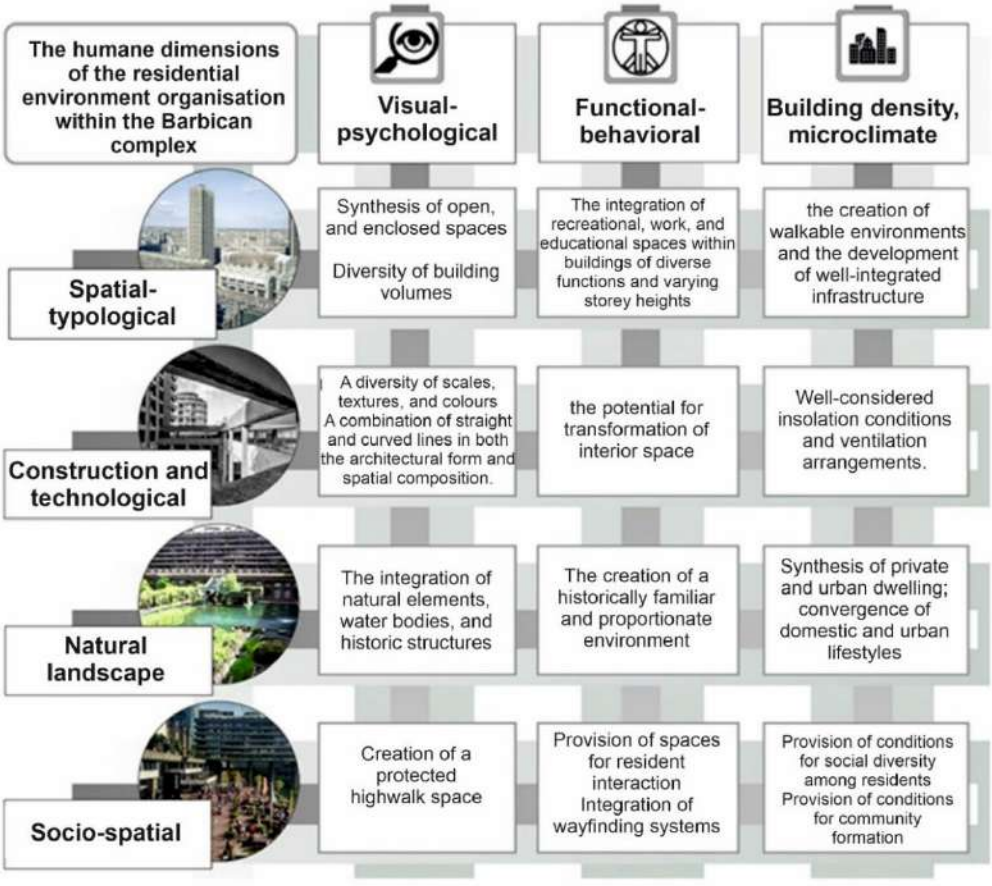


Figure 3 – The Humanitarian aspects of organizing the residential environment of the Barbican Complex (author's material)

The duration of construction and the shift in societal priorities regarding the Brutalist style in the early 1980s led to criticism of the residential complex. However, despite the critical responses, the experiment in creating a comfortable living space for urban dwellers was hugely successful, both among residents and architects worldwide. The alienating architecture of the complex's buildings, combined with the carefully considered organisation of the living environment, provides residents with conditions that are distant from the realities of the noisy, fast-paced urban life. It fosters a sense of community and safety while simultaneously creating a comfortable living environment. From this perspective, one can conclude that a comfortable and humane living environment in an urban residential complex should possess qualities such as architectural, spatial, and planning diversity, the inclusion of natural elements, and a clear focus on the feelings and perceptions of the individual **(Figure 3)**.

5 CONCLUSIONS

The diversity in the volumetric and spatial planning solutions of the Barbican residential complex's living environment is achieved through the harmonious combination of open and enclosed spaces, interior and exterior design elements, and the incorporation of natural elements, despite the monotonous concrete construction typical of the Brutalist style. This thoughtful and meticulously planned organisation of the living environment ensures a comfortable space for living, recreation, and work.

Approximately 60 years after the construction of this large residential complex, the following observations can be made:

1. contrary to the usual tendency for residential areas to be pushed out from city centres, a large residential district has been established in central London, alleviating its residents from many of the negative issues typically associated with living in an intensively functioning city centre;
2. despite the unpopularity and seemingly inappropriate nature of Brutalism for residential buildings, the Barbican area remains highly popular and demonstrates a high level of functionality across all of its zones;
3. the concept of a 'fortress' did not result in a rigid separation from surrounding areas. Instead, it manifested in the clear and successful functional division of residential, pedestrian, and recreational zones from traffic routes, car parks, and other service functions. The Barbican is open for visits and walks not only to its residents but also to anyone wishing to enjoy it. Thus, the complex is fully integrated into the urban environment. Despite being located in the historical centre of a large metropolis, it provides its residents with conditions comparable to living in a green suburban area, which means that the desired comfort and quality of life have been achieved at a sustainable level.

The humane aspects of the Barbican residential environment can be identified as:

1. architectural and typological diversity and a comfortable scale;
2. the recognisability and identity of the complex, blending old and new elements;
3. a high level of natural elements;
4. high-quality landscaping;
5. a well-developed infrastructure.

The modernist architecture of the Barbican residential complex continues to attract people primarily due to its carefully considered organisation of the living environment. Despite the Brutalist style being ostracised by residents and architects in many countries, due to numerous unsuccessful projects, the Barbican estate demonstrates how the harmonious combination of architecture, design, nature, and society (active community) can be a successful realisation of utopian architecture, both comfortable and in demand for many years.

Today, the Barbican is considered a significant architectural achievement and has been designated as a Grade II listed building due to its architectural interest, scale, planning, and social cohesion. It is no coincidence that Queen Elizabeth II, during the complex's opening in 1982, referred to it as one of the wonders of the modern world. The living environment of the Barbican continues to be highly sought after, providing not only comfortable living spaces for its residents but also attracting local citizens and numerous tourists.

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REVIEW ARTICLE

FORMATION OF STYLE IN THE RESIDENTIAL ARCHITECTURE OF ALMATY IN THE 1930S–1950S: SEARCH FOR A NEW COURSE AND THE PROBLEM OF CHOICE

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Abstract. *Alongside the urgent need to address large-scale urban population growth and adapt housing to the natural and climatic conditions of the region, the first attempts to incorporate elements of the national architectural heritage emerged from the mid-1930s in Almaty, leaving a distinctive mark on the city's residential architecture. Through the analysis, generalisation, and synthesis of theoretical and historical sources - primarily the works of architects and eyewitness researchers of the period -this study explores the directions of theoretical searches for a new architectural course in connection with the formation of Kazakhstan's regional style. Examples of residential buildings in Almaty of the 1930s and early 1950s are presented to illustrate the practical embodiment of the "synthesis of the arts", reflected in regional elements of residential architecture and in the broader organisation of the city's living environment. The article examines methods of shaping the residential environment in Almaty and identifies approaches to creating a harmonious, identity-reflective urban environment through regional stylistic features. These include the incorporation of architectural details such as cornices, balconies, and loggias; landscaping and irrigation of residential quarters; the integration of ornamental compositions as a link with national cultural traditions; and, more generally, the creation of coherent urban ensembles and interiors. The findings of the study may be applied to the contemporary formation of the residential environment of modern Almaty.*

Keywords: *housing architecture, regional style, synthesis of arts, urban living environment, Almaty.*

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ШОЛУ МАҚАЛА

1930–1950-ЖЫЛДАРЫ АЛМАТЫНЫҢ ТҰРҒЫН ҮЙ СӘУЛЕТІНДЕ СТИЛЬДІҢ ҚАЛЫПТАСУЫ: ЖАҢА БАҒЫТТЫ ІЗДЕУ ЖӘНЕ ТАҢДАУ МӘСЕЛЕСІ

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Аңдатпа. *Қала тұрғындарының ауқымды өсуі және тұрғын үй құрылысын аймақтың табиғи-климаттық жағдайына бейімдеу мәселесін шұғыл шешу қажеттілігімен қатар, 1930 жылдардың ортасында Алматыда ұлттық сәулет өнерінің элементтерін пайдаланудың алғашқы талпыныстары пайда болды, бұл қаланың тұрғын үй сәулетінде елеулі із қалдырды.Сипатталған уақыт кезеңінің сәулетшілері мен зерттеуші – куәгерлері жариялаған теориялық және тарихи материалдарды талдау, жалпылау және синтездеу негізінде Қазақстанның өңірлік стилінің ерекшеліктерімен өзара байланыста жаңа архитектуралық бағытты теориялық іздестіру бағыттары айқындалады. Мақалада келтірілген 1930-шы жылдар мен 1950-ші жылдардың басындағы Алматы тұрғын үй ғимараттарының мысалдары тұрғын үй архитектурасының аймақтық элементтерінде және қаланың тұрғын үй ортасын ұйымдастыруда көрініс тапқан өнер синтезінің практикалық көрінісін көрсету қажеттілігімен байланысты. Мақалада Алматының тұрғын үй ортасын қалыптастыру тәсілдері талданады және сәулет элементтерін тұрғын үй ғимараттарына– карниздерді, балкондарды, лоджияларды бейнесіне қосу; тұрғын аудандарды суландыру және көгалдандыру мәселелерін шешу; ұлттық мәдени дәстүрмен байланыс элементтері ретінде сәндік композицияларды қосу сияқты өңірлік стильдің аспектілері арқылы халыққа бірдей үйлесімді тұрғын үй ортасын ұйымдастыру тәсілдері айқындалады, жалпы, қалалық ансамбль мен қалалық интерьерді құру. Зерттеудің алынған нәтижелері қазіргі Алматы қаласының тұрғын үй ортасын қалыптастыру кезінде одан әрі пайдаланылуы мүмкін.*

Түйінді сөздер: *тұрғын үй сәулеті, аймақтық стиль, өнер синтезі, қалалық өмір сүру ортасы, Алматы.*

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ОБЗОРНАЯ СТАТЬЯ

ФОРМИРОВАНИЕ СТИЛЯ В ЖИЛИЩНОЙ АРХИТЕКТУРЕ АЛМАТЫ 1930–1950-Х ГОДОВ: ПОИСК НОВОГО КУРСА И ПРОБЛЕМА ВЫБОРА

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Аннотация. *Наряду с острой необходимостью решения проблемы масштабного роста городского населения и адаптации жилищного строительства к природно-климатическим условиям региона, именно с середины 1930-х годов в Алматы появились первые попытки использования элементов национального архитектурного наследия, что оставило заметный след в жилой архитектуре города. На основе анализа, обобщения и синтеза теоретических и исторических материалов, преимущественно опубликованных зодчими и исследователями – очевидцами описываемого периода времени, выявляются направления теоретических поисков нового архитектурного курса, во взаимосвязи с особенностями регионального стиля Казахстана. Приведенные в статье примеры жилых зданий Алматы 1930-х и начала 1950-х гг. обусловлены необходимостью продемонстрировать практическое воплощение синтеза искусств, который нашел отражение в региональных элементах архитектуры жилища и организации жилой среды города. В статье анализируются приемы формирования жилой среды Алматы и выявлены подходы организации гармоничной, идентичной жилой среды посредством таких аспектов регионального стиля, как включение архитектурных элементов в образ жилого здания – карнизов, балконов, лоджий; решение вопросов обводнения и озеленения жилых кварталов; включение орнаментальных композиций в качестве элементов связи с национальной культурной традицией, и, в целом, создании городского ансамбля и городских интерьеров. Полученные результаты исследования могут быть использованы в дальнейшем при формировании жилой среды современного города Алматы.*

Ключевые слова: *жилищная архитектура, региональный стиль, синтез искусств, городская среда обитания, Алматы.*

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CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

During the preparation of this manuscript, the authors used artificial intelligence tools (ChatGPT) solely for editorial assistance, such as improving phrasing and checking grammar, spelling, and punctuation. All ideas, interpretations, and conclusions are the responsibility of the authors, who take full accountability for the content of the article.

АЛҒЫС / ҚАРЖЫЛАНДЫРУ КӨЗІ

Зерттеу жеке қаржыландыру көздерін пайдалана отырып жүргізілді.

МҮДДЕЛЕР ҚАҚТЫҒЫСЫ

Авторлар мүдделер қақтығысы жоқ деп мәлімдейді.

Мақаланы дайындау барысында авторлар жасанды интеллект құралдарын (ChatGPT) тек редакциялық көмек мақсатында пайдаланды: тұжырымдарды жетілдіру, грамматикалық, орфографиялық және тыныс белгілеріндегі қателерді тексеру үшін. Барлық идеялар, интерпретациялар мен қорытындылар авторларға тиесілі, және олар мақаланың мазмұнына толық жауапты.

БЛАГОДАРНОСТИ/ИСТОЧНИК ФИНАНСИРОВАНИЯ

Исследование проводилось с использованием частных источников финансирования.

КОНФЛИКТ ИНТЕРЕСОВ

Авторы заявляют, что конфликта интересов нет.

При подготовке рукописи авторы использовали инструменты искусственного интеллекта (ChatGPT) исключительно для редакторской поддержки: корректировки формулировок, проверки грамматических, орфографических и пунктуационных ошибок. Все идеи, интерпретации и выводы принадлежат авторам, которые несут полную ответственность за содержание статьи.

1 INTRODUCTION

The 1932 resolution, entitled "On the Restructuring of Literary and Artistic Organizations", gradually influenced the development of Almaty, albeit with some delay compared to the European part of the USSR. The neoclassical style, through which architects sought to define a "universal, timeless architectural language" **(Selivanova, 2010)**, was closely aligned with the adopted ideology and readily accepted by the broader public. The architectural shifts of this period were intrinsically connected to the transformation of socio-political ideals, which shifted from utopian aspirations toward a more pragmatic focus on economic survival **(Han-Magomedov, 2010)** and competition with capitalist nations. Soviet state authorities strategically consolidated political power, aiming to regulate the economy and shape social dynamics **(Kassymbekova, 2017)**. This alignment of architecture with state objectives fostered the consolidation of totalitarian and authoritarian systems, with construction activities entirely funded by the state. Art and architecture were proclaimed the principal instruments of Soviet power and ideology. The avant-garde movement virtually ceased to exist, as functional architecture was declared illegal and banned **(Starostenko, 2021)**. It can be noted that the construction of projects with elements of the neoclassical style was relevant in Kazakhstan from the mid-1930s to the second half of the 1950s **(Pronina, 2020)**.

It is important to emphasize that, when designing and discussing issues of residential architecture in the press or in speeches at Congresses, soviet architects paid wide attention to developments in the field of dwelling construction in the countries of Europe and America for example, in such issues as: residential arrangement, its functional-planning organization, placement of a car in the structure of a house, differences in building standards, identifying positive aspects that can be applied in Soviet design practice or, conversely, criticizing issues that are not suitable for adoption. For this study, the works of soviet and Kazakhstan's architects were important: Ginzburg M., Shchusev A., Mendykulov M., Basenov T., Glaudinov B. A., as well as the articles that began to appear mainly in the periodical press (for example, Kalmykov V., Lavrov V., Rempel L.) about traditional techniques and methods of building houses in Central Asia, the principles of organization that were regarded as potentially adaptable to new construction **(Zhalmagambetov et al., 2024)**.

The objective of the article is to present a comprehensive picture of the prerequisites, directions and outcomes of the search for a new regional style (where a regional style is a materialized subject-spatial object created on the basis of a cultivated aesthetic image and a way of life in a given area) in the architecture of a Kazakhstan's urban residential of the 1930-1950s, as an integral part of the model of a comfortable urban living environment in Almaty in conjunction with theoretical research by soviet architects (on the synthesis of arts in architecture) and the ideological situation of the considering period **(Akhmedova, 2016; Akhmedova, 2020; Akhmedova et al., 2022)**.

Revisiting this past - particularly the most vivid stage in the search for a national style, is highly relevant in our time, when the borders of Almaty are expanding, and the problems of a well-thought-out organization of a living environment identical to the people, corresponding to climatic conditions, emphasizing the conditions of the area and life, are becoming more and more relevant every year **(Glaudinov et al., 1987; Samoilov, 2003; Karatseyeva et al., 2025)**.

2 LITERATURE REVIEW

The design practice of the early 1930s began with critical views on the architecture of the previous period. Avant-garde architecture in the Soviet Union was labeled bourgeois. However, the core of soviet architecture was still "state property, a state order and an ideological orientation" **(Kalashnikov, 2010)**. A series of resolutions led to a decline in scientific and creative discussions of architectural problems, which were entirely under the control of the authorities.

In 1929, Almaty received the status of the republic's capital. Architects were tasked with creating the image of a large capital city of Kazakhstan – the capital of the Union Republic **(Posocco & Akhmedova, 2016)**. In Kazakhstan, the first design office, Kazgosproekt, opened in October 1930. **(Glaudinov et al., 1987)**. In 1932, the Union of Soviet Architects was established – a unifying unit of previous architectural movements and groups. This year marked a turning point in the development of Soviet architecture, which led to a complete revision values of society and ideas about the aesthetic ideal of architecture.

The main prerequisites included: the limited quantity and low quality of residential buildings, the dominance of "box" architecture, homogeneous development – the inability of the new architecture to express the real expectations and needs of society, the poverty of figurative language and the "nihilistic attitude (of architects) to architectural values" **(Soviet architecture, 1934)**. Researchers also named the following prerequisites for choosing a new style of the architectural movement: the need for the style to be close to nature **(Shchusev, 1935)** and "plainness" accessible to the people; the opportunity to realize creative abilities, where "the classics give wide scope to fiction, pathos in the field of architectural creativity" **(Munc, 1940)**; the universality of the language of forms, which with equal success ensured to represent both bourgeois democracies and totalitarian regimes, and was used to express the ideas of a socialist utopia. In addition, the new style was necessary for the authorities as a means of unifying an architectural activity.

In this period, the primary role was given not to residential construction, but to monumental public buildings and infrastructure facilities. At the same time, the search for an architectural socialistic image of new residential buildings **(Marcomini, 2024; Meuser & Khmelnitsky, 2021)** and planning solutions for apartments continued, however, on a smaller scale compared to the twenties. However, in practice, design and construction according to the new rules of architectural creativity found expression in the formation of an urban dwelling mainly from the aesthetic side **(Samoilov, 2005)**.

The main goals that the architects set were:

- overcoming the consequences of the form-creation of the previous period;
- critical mastering of the historical heritage **(Vas'kin & Nazarenko, 2009)**.

Soviet architects saw the task of the new architectural style in creating an artistic image through the synthesis of arts **(Bachynska, 2021)**. This image was to be interpreted from the position of social prerequisites, as a concept "complex and subtle, rather than the concept of pure rhythm and bare construction" **(Lazarev, 1937)**, that is, to focus the search on the general volumes of the house, where with successfully found "proportions of spans, supporting pylons - no decoration of the wall with ornamentation or sculpture will be required" **(Fomin, 1933)**. At the same time, the fundamental principles of classical architecture, which were not entirely the subject to imitation, but implied rethinking in accordance with the requirements of the era; in the fight against eclecticism, the search for new forms and new content, which "must be understood in development dialectically, ideologically and artistically as well" **(Vesnin, 1933)**, through a creative functional method **(Ginzburg et al., 1934)**, reflected the unity of goals, means and architectural image. Ginzburg defined the tasks of the architects of the era as follows: "To find the correct relationship between the elements of knowledge and science, to invent an artistic image on their basis, to find a synthesis of what previous eras demolished, to equip themselves in order to be able to fulfill the social order of the era" **(Ginzburg, 1933)**. In other words, the aim was to create both a materially and aesthetically comfortable environment for human living.

Drawing a parallel between the architectural theme of the classical world **(Shchusev, 1937)**, which was closely connected with the folk epos and the mythology of the worldview, the architect A. Shchusev concluded that the folk epic should be included in modern architecture, but with the note "its own": "its own heroism and its own lyricism", thereby emphasizing the importance of searching for means of national identity of architecture. The architect determined that "our heroism was the heroism of free labor, and lyricism was the one of a joyful life". Shchusev A. also believed that the mechanical transfer of the classical heritage would give results only in conjunction with the existing worldview and ideology. This condition was expressed through the inclusion of modern attributes of the era in the art sphere in architecture - if sculptural, then of a soviet worker, and in the post-war period – the attributes of a defender, if in painting - the image of peace and harmony of the people who held victory. The inclusion of ornament and decoration in the consideration the issue of searching for the style of architecture of Kazakhstan was reflected in the synthesis of arts, where painting, sculpture and sculptural decorative elements acted as ornament **(Glaudinova et al. 2019)**.

The search for the aesthetic imagery of the building was not limited to decorative expression alone. Architects emphasised the importance of constructive means. In the architecture of a residential building, the main elements were to be “window openings, doors, balconies and bay windows, that is, the elements which are distinctive for a dwelling. Logically developing this concept, the architect must seek ways to create a new architectural style” **(Shkvarikov, 1941)** including rethinking the original principles of construction and architecture. Architects needed to learn to adopt the knowledge of builders, their ability to understand the native landscape, the local nature, and the principles of creating complex pictorial compositions.

It is important to note that the architecture of the considering period was perceived by the authorities as a means of introducing social ideas into the consciousness of the “national masses” and had to be implemented “... in familiar, clear and understandable forms that appeal to the nationality for which it was intended” **(Kolotkov, 1935)**. Thus, it functioned as a link between the architect-designer and the people, where the national style was reflected through the integration of classical and traditional architecture **(Glaudinov et al., 1987; Samoilov, 2004)**. It was assumed that national architecture was most understandable to the people, and its essential features were the truthfulness and clarity of the architectural-spatial image, harmony with nature and with the social and everyday environment.

The centuries-old construction culture that was formed in the climatic conditions of Central Asia and Kazakhstan developed distinctive compositional methods, traditions and techniques that were reflected in vernacular architecture. Pre-revolutionary housing types in many Central Asian settlements shared common features that reflected the conditions of life (where the house was a hearth inaccessible to the gaze of others) – which was architecturally reflected in the complete isolation of the plan, the presence of one street entrance and blank walls surrounding a folk dwelling. In examining the traditional dwellings of the peoples of Central Asia, the architect V. Kalmykov **(Kalmykov, 1934)** identified the obvious need for new construction to reorganize the social and everyday basis of a dwelling and to reveal it in a new interpretation, using the basic compositional principles of architectural refinement of the external volume and internal spaces of folk dwellings of the region (for example, division into summer and winter parts, inclusion of internal courtyards, the contrast of almost blank walls and terraces, open and semi-open (iwans) rooms - recessed loggias, awnings, balconies).

Architects **(Dwelling architecture issues, 1936)** increasingly raised the question of the ensemble, according to which the image of a residential building should reflect the principles of spatiality and plasticity, due to the introduction of national elements into architecture. It was assumed that the principle of spatiality in the architecture of a residential building could be expressed through the richness of light and shade and the introduction of loggias, terraces, balconies, cornices and other details into the architecture of the house, creating a game of light and shade on the facade of the building. In the architecture of the East, according to Professor Rempel L. - the leading role belonged to the problem of light - from internal spaces to external planes of buildings, as well as - compliance with shadow protection and the spread of green areas, fountains, irrigation ditches in the urban environment.

The founder of architectural science in Kazakhstan, a professor of architecture Mendikulov Malgabar believed that the inclusion of traditional elements in the architecture of Kazakhstan “is appropriate in the conditions of a southern city and give variety, picturesqueness and the necessary shading to facades and other parts of the building” **(Baragin & Belocerkovskij, 1950)**. Meanwhile, the development of architectural and artistic heritage in the capital of the Kazakh SSR occurred from “generalized regional to finely differentiated national in combination with internationally interpreted order forms” **(Mendikulov, 1953; Margulan et al., 1959; Samoilov, 2002)**. However, in the post-war period the widespread use of classical orders in synthesis with national motifs in Almaty frequently resulted in eclectic or archaic outcomes.

3 MATERIALS AND METHODS

The research methodology is based on a comprehensive approach, which involves analysis, generalization and synthesis of literary, historical publications and articles. The selected sources, that were taken into consideration, touched the research topic, which was aimed at finding a new regional style for the formation of the residential environment of the city and an urban dwelling of Almaty in the 1930s - early 1950s from the point of view of the synthesis of arts, as a process of combining arts (including traditional elements and techniques of organizing a national dwelling) into a single artistic unit. Those sources, that most fully met the purpose and objectives of the article, were selected as cited materials.

In the context of the research, the following tasks had to be solved:

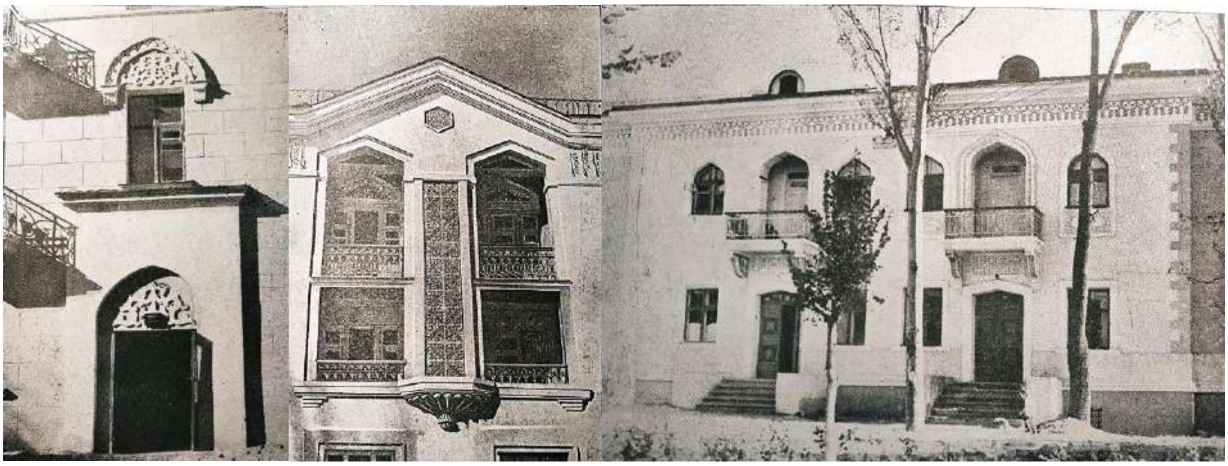
- to identify the most complete understanding of the prerequisites, directions and results of the search for a regional style, mainly in theoretical studies and publications of architects of the 1930-1950s;
- to trace the relationship between theory and practice, through the given examples of dwelling organization and the formation of the living environment of Almaty in the considering period.

4 RESULTS AND DISCUSSIONS

In general, the large-scale development of residential buildings in Almaty during this period was concentrated along the city's main arterial roads - Furmanov, Kalinin, Stalin - the central arterial roads of the city. The dominant compositional approach was district-based development. In the organization of the city district, the task was to use the spatial solutions of folk architecture, taking into account the living and natural-climatic conditions. On the whole, in this period, the district began to be defined not as an isolated unit, but as part of the city system (acting as a group of residential complexes and as a group of residential districts surrounded by arterial roads). The development of the enlarged blocks of Almaty had to be necessarily linked to urban development tasks and combined with the tasks of improving a dwelling - landscaping, watering, connecting the house with the site - it was believed that such measures would most fully solve the problem of the architectural and artistic image of a residential building **(Murzabayeva et al., 2022)**. At the same time, the silhouette had to be not sharply contrasting, but harmonious, thus creating a memorable architectural image. The practical implementation of the described techniques allowed the newly built dwellings to be harmoniously integrated into the structure of new urban areas, creating chamber protected spaces of residential districts and maintaining a visual connection with the distinctive foothill landscape **(Pakina & Batkalova, 2020)**.

Meanwhile, a separate residential building, organically fitting into both the architecture of the square and the main city road, had to replicate "the compositional principles of the ensemble in miniature - centricity, symmetry, weighting towards the bottom" **(Hmelnickij, 2006)**, and had to include elements of facade decoration in the architecture - the introduction of bas-reliefs, architectural decorative elements (arches, cornices, balconies, rustication), mosaics and paintings with a new socialist theme or newly rethought ornaments **(Figure 1a, b)** as decoration of external facades. Among the traditional elements in the architecture of Almaty dwelling were pointed arch, domes of different shapes, portal-pishtaq, recessed entrances and loggias, blind plane of the wall **(Nussipkozhaeva, 2020)**. Decorative treatments extended further to figured brickwork, ceramic cladding, and the widespread use of ornamental stone carving **(Karpykov & Kakorin, 1980)**, alabaster, and woodwork in ornamental compositions.

Along with the ornament, decorative functions in the residential architecture appeared to be structural elements as well; they were specific for folk architecture, mainly those that best embodied the concept of "oriental style", but interpreted in a unique way. According to **Figure 1**, in it can be noted that in the design of the facade of the House of the Ministry of Water Management (architect Bapishev, 1950), such techniques as national ornament, lancet windows on the second floor, balconies with metal grilles and figured brackets were reflected. These techniques were a part of the creation of an identical living environment - they reflected the reworked forms of traditional architecture in combination with the use of new building materials and the use of new technology in construction **(Medykulov, 1953; Abdrassilova & Aukhadiyeva, 2025)**.



a) b) c)

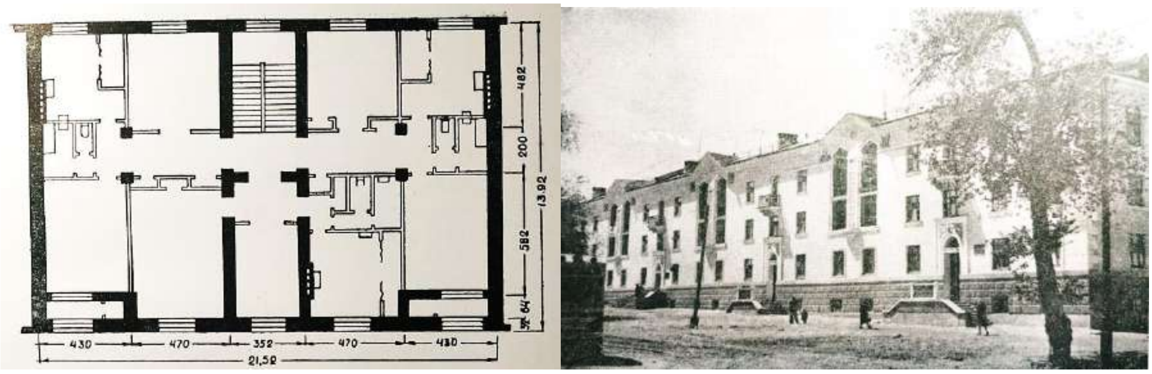
Figure 1 – Traditional elements of architecture in the residential architecture of Almaty in the 1930s-1950s.: a) fragment of the southern facade of the Ninth dwelling complexes; b) fragment of the eastern facade of a residential building on Uigurskaya Street; c) the northern facade of a semi-detached residential building of the House of the Ministry of Water Management (architect Bapishev), 1950. **(Baragin & Belocerkovskij, 1950)**

The period of creative exploration was reflected in the widespread use of porticoes, pediments, cornices, which decorated residential buildings in Almaty. At the same time, despite the rich decor and wide use of bay windows, loggias and balconies in the architecture of residential buildings as an integral part of a national dwelling, the architect Basenov believed that in such residential buildings before 1946, the rich architectural national heritage and folk art were not considered enough **(Basenov, 1951)**. The emphasis in the search for regionalism was reduced to attention to the decorative design of external solutions, while the planning solutions for apartments, for the most part, remained typical and did not take into account either demographic or national traditions of life **(Sarzhanov & Schurch, 2023)**.

Soviet architects maintained that the study of architectural heritage for imitation and adoption should include not only Greek and Roman motifs (international order forms), elements and composition of the building facade, but also modern architecture of America and Europe, which was expressed in the adoption of technical, design principles, and methods of the most rational use of building materials. There were also opinions that in the “search” for a new course it was necessary to include in the legacy fifteen years after the revolution: namely, “open, ventilated courtyards…, the necessary provision of natural light to living premises… the elimination of single-story buildings” **(Fomin, 1933)**. Thus, the question of the necessity of combining the results of innovative experiments of the past period with historical national and world experience arose acutely. At the same time, it was necessary not only to “assimilate” all the results of both historical periods and modern times (positive developments of foreign countries), but also to understand them and even surpass them. With regard to the architecture of Almaty dwelling, such “understanding” was reflected through the selection of the most rational principles from traditional architecture: by including architectural and decorative details, ornamentation, and rethinking of traditional methods of organizing a dwelling, and the combination of these principles with the latest achievements - in the development of technology and everyday culture **(Akhmedova et al., 2022)**. The use of decoration and the stylization of the order system required the appropriate proportioning of architectural details, as a result of which the external appearance of residential buildings became more solid and large-scale **(Akhmedova, 2009)**.

Figure 2 illustrates a project of a forty-apartment residential building on Uygurskaya Street, Gogolya Street, Mechnikov Street, and Yunyh Kommunarov Street, which is successfully oriented to the cardinal points, where the kitchens and staircases were located on the western side of the building.

The apartments were equipped with built-in closets and a bathroom with a shower. The three-story building included loggias “recessed” behind the building’s façade line – important elements of a southern dwelling. The layout of the apartments called for through and corner ventilation. The facades reflected motifs of national architecture and ornamentation, embodied in the stucco motifs of the entrances and window openings, and in the architraves. The portals-entrances were designed in the form of a pointed arches.

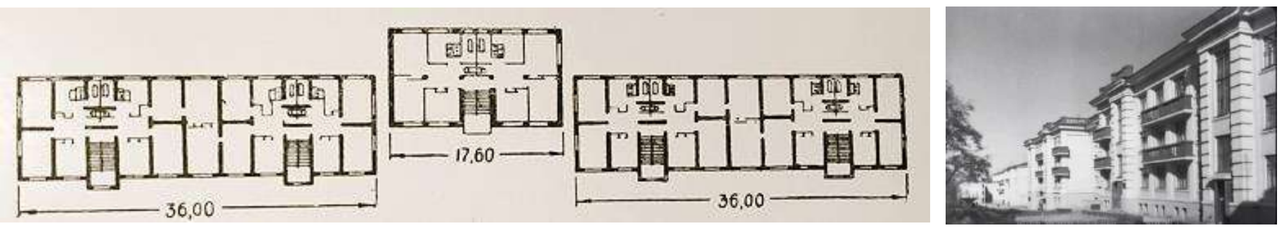


a) b)

Figure 2 – House on Uygurskaya Street (architect Bobovich), 1951-1952: a) second floor plan, section; b) the eastern facade of the building **(Medykulov, 1953)**

Soviet architects have repeatedly noted the importance of the issues of ensemble, composition, standardization, but in practice, to a large extent, everything was limited to the consideration of any of the listed aspects of a dwelling design. Only in a few cases all aspects of one architectural theme merged into a single composition. In this case, the house became a real object, successfully included in the whole ensemble, associated with nature, terrain, space **(Alexander, 2020)**. In Almaty, such examples can be called the buildings of dwelling complexes along Furmanov Street (a drawing of the plan of the second floor and a fragment of the facade of the second dwelling complex are presented in **Figure 3**).

The placement of residential complexes of this period of construction in Almaty (the second – the ninth), created by architects according to individual projects, made it possible to create a single deep-spatial composition **(Akhmedova, 2009)**. Residential buildings not only formed a holistic composition of the city's block development but also fenced off the interior spaces of courtyards from streets and roads, thereby serving as a powerful compositional tool for ensuring competent functional zoning. The characteristic features of the composition were: the formation of a holistic facade part of the street and the creation of a system of open comfortable spaces and territories, interconnected by means of architecture and design: taking into account the terrain (stairs, retaining walls, safe descents were thought out); considering the opposition of the complex of buildings to natural and climatic conditions through landscaping, inclusion of fountains and placement of dwelling complexes in accordance with historically formed architectural planning and urban planning solutions; design elements - by decorating courtyard spaces with small architectural forms. Large apartment blocks were arranged in block-by-block development, forming a residential complex with the necessary courtyard and the service part: retail and storage facilities in the basement.



a) b)

Figure 3 – dwelling complexes (Zhilkombinaty) no 2 (architect Borisenko): a) second floor plan; b) fragment of the facade, photo **(Medykulov, 1953)**

Figure 4 clearly illustrates that the residential buildings in the historic districts of modern-day Almaty still preserve elements of the architectural and artistic explorations pursued by architects of the 1930s. These are visible in the ornamental decorations of facades—ceramic panels, uniquely interpreted national motifs, elaborately crafted column capitals and pilasters, cornices, spires, friezes, window surrounds, ceramic inserts, balcony railings, and the artistic-architectural treatment of entrance features found on Seifullin Avenue, Abilaykhan Avenue, Gogol Street, Tole Bi Street, Kunayev Street, Mailin Street, among other prominent thoroughfares.

a) b) c)

Figure 4 – Methods for organizing the living environment: a) the spire in the architecture of the Turksib workers' apartment building (architect Il'enko); b) fragment of the facade of the House of Scientists (architect Bobovich); c) arch portal in the architecture of the residential building for specialists of the Kirov Plant (architect Bobovich) (author's material).

5 CONCLUSIONS

The synthesis of arts became a significant means of expressing the style of Soviet architecture, shaping ideology, the city, and even the everyday life and perception of citizens. s. Mainly, the synthesis of arts through the search for regional architecture in Almaty meant the decoration of architectural objects with the help of painting and ornament, but one can note a broader area - the synthesis of architecture and design, where design materialises the cultural measure of history. The main goal of this synthesis of arts in the formation of residential architecture in the city of Almaty is the organisation of a harmonious, people-identical environment of new urban territories, which was reflected in the following approaches:

1. careful organisation of apartments adapted to climatic conditions - ventilation, placement of rooms in the structure of the apartment according to the cardinal points, inclusion of traditional elements of folk architecture - loggias and balconies;
2. integration of housing with the urban environment, for example, through the inclusion of small architectural forms: skillfully ornamented lampposts, fountains, flowerpots (along Kabanbai Batyr Street, Zhandosov Street, etc.), which were an integral part of the composition of the city and the residential environment;
3. thoughtful solutions to issues of creating green spaces, watering of residential areas, and maintaining a visual connection with the unique foothill landscape;
4. extensive use of ornamental compositions in the architecture of a residential building;
5. attempts to create an urban ensemble and urban interiors, creating chamber, protected spaces of residential areas.

Theoretical guidelines and attempts at practical integrated design of the urban living environment, incorporating elements of national heritage through the synthesis of architecture and design, established the humanistic orientation of architecture towards its inhabitants. These became important prerequisites for further research into the organisation of urban dwellings and the creation of a comfortable living environment in Almaty.

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REVIEW ARTICLE

3D PRINTING IN THE ARCHITECTURE OF KAZAKHSTAN: FROM EXPERIMENTAL HOUSES TO SUSTAINABLE SOLUTIONS

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Abstract. *The analysis of the potential of introducing 3D printing technology into the architectural and construction practice of the Republic of Kazakhstan includes examples of the implementation of 3D-printed buildings both in the international arena (the Netherlands, Angola) and in Kazakhstan. The article considers the possibility of introducing 3D printing into national practice with an emphasis on sustainability, adaptability and energy efficiency. The purpose of the study is to assess the technological readiness and practical applicability of 3D-printed solutions in the context of Kazakhstan. The work uses a comparative analysis of international and domestic projects, a review of relevant literature, a study of the engineering characteristics of materials and mixtures, as well as interviews with specialists. Projects such as Milestone, Power2Build, and local implementations using COBOD printers are considered as the main examples. The advantages of 3D-printed solutions using local materials are revealed: reduction of construction time and labor costs, improvement of thermal engineering parameters of enclosing structures and reduction of carbon footprint. The ability of the technology to form complex geometries, provide integrated thermal insulation and adapt to earthquake-prone conditions is shown. The prospects of biodegradable composites and digital workflows (BIM/CAM, parametric design) are noted. 3D printing has already moved into the category of applied technologies ready to scale in Kazakhstan, subject to standardization of formulations, development of a regulatory framework and training of personnel. The technology offers economic and environmental benefits, especially for remote and seismically hazardous regions, and can become a tool for mass sustainable housing construction. The authors offer recommendations on the adaptation of mixtures to climatic conditions, the development of standards and the integration of educational programs to accelerate the introduction of technology and ensure the quality of construction. Further research should focus on the durability of printed structures and the economic assessment of large-scale projects.*

Keywords: *3D printing, architecture, sustainable construction, adaptability, biodegradable materials, energy efficiency, digital design*.

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ШОЛУ МАҚАЛА

ҚАЗАҚСТАН СӘУЛЕТІНДЕГІ 3D-БАСПА: ЭКСПЕРИМЕНТТІК ҮЙЛЕРДЕН ТҰРАҚТЫ ШЕШІМДЕРГЕ ДЕЙІН

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Аңдатпа. *Қазақстан Республикасының сәулет және құрылыс практикасына 3D-баспа технологиясын енгізу әлеуетін талдау халықаралық аренада (Нидерланды, Ангола), сондай-ақ Қазақстанда 3D-баспа ғимараттарын іске асыру мысалдарын қамтиды. Мақалада тұрақтылыққа, бейімделуге және энергия тиімділігіне назар аудара отырып, ұлттық тәжірибеге 3D басып шығаруды енгізу мүмкіндігі қарастырылады. Зерттеудің мақсаты-Қазақстан контекстінде 3D-баспа шешімдерінің технологиялық дайындығы мен практикалық қолданылуын бағалау. Жұмыста халықаралық және отандық жобаларды салыстырмалы талдау, бейіндік әдебиеттерге шолу, материалдар мен қоспалардың инженерлік сипаттамаларын зерттеу, сондай-ақ мамандармен сұхбат пайдаланылды. Негізгі мысалдар ретінде Milestone, Power2Build сияқты жобалар, сондай-ақ COBOD принтерлерін қолдана отырып жергілікті іске асыру қарастырылады. Жергілікті материалдарды пайдалану кезінде 3D басып шығару шешімдерінің артықшылықтары анықталды: құрылыс мерзімдері мен еңбек шығындарын қысқарту, қоршау конструкцияларының жылу техникалық көрсеткіштерін жақсарту және көміртегі ізін азайту. Технологияның күрделі геометрияны қалыптастыру, интеграцияланған жылу оқшаулауын қамтамасыз ету және сейсмикалық қауіпті жағдайларға бейімделу қабілеті көрсетілген. Биологиялық ыдырайтын композиттер мен цифрлық жұмыс процестерінің (BIM/CAM, параметрлік дизайн) болашағы атап өтілді. 3D-басып шығару құрамдарды стандарттау, нормативтік базаны әзірлеу және кадрларды даярлау шартымен Қазақстанда масштабтауға дайын Қолданбалы технологиялар санатына енді. Авторлар технологияны жеделдетіп енгізу және құрылыс сапасын қамтамасыз ету үшін қоспаларды климаттық жағдайларға бейімдеу, стандарттарды дамыту және білім беру бағдарламаларын біріктіру бойынша ұсыныстар ұсынады. Әрі қарайғы зерттеулер басылған конструкциялардың беріктігіне және ауқымды жобаларды экономикалық бағалауға бағытталуы керек.*

Түйін сөздер: *3D басып шығару, сәулет, тұрақты құрылыс, бейімделу, биологиялық ыдырайтын материалдар, энергия тиімділігі, цифрлық дизайн.*

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ОБЗОРНАЯ СТАТЬЯ

3D-ПЕЧАТЬ В АРХИТЕКТУРЕ КАЗАХСТАНА: ОТ ЭКСПЕРИМЕНТАЛЬНЫХ ДОМОВ К УСТОЙЧИВЫМ РЕШЕНИЯМ

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Аннотация. *Анализ потенциала внедрения технологии 3D-печати в архитектурную и строительную практику Республики Казахстан включает примеры реализации 3D-печатных зданий как на международной арене (Нидерланды, Ангола), так и в Казахстане. В статье рассматривается возможность внедрения 3D-печати в национальную практику с акцентом на устойчивость, адаптивность и энергоэффективность. Цель исследования - оценить технологическую готовность и практическую применимость 3D-печатных решений в контексте Казахстана. В работе использованы сравнительный анализ международных и отечественных проектов, обзор профильной литературы, изучение инженерных характеристик материалов и смесей, а также интервью со специалистами. В качестве основных примеров рассмотрены такие проекты, как Milestone, Power2Build, а также локальные реализации с применением принтеров COBOD. Выявлены преимущества 3D-печатных решений при использовании местных материалов: сокращение сроков строительства и трудозатрат, улучшение теплотехнических показателей ограждающих конструкций и снижение углеродного следа. Показана способность технологии формировать сложную геометрию, обеспечивать интегрированную теплоизоляцию и адаптироваться к сейсмоопасным условиям. Отмечена перспективность биоразлагаемых композитов и цифровых рабочих процессов (BIM/CAM, параметрический дизайн). 3D-печать уже перешла в разряд прикладных технологий, готовых к масштабированию в Казахстане при условии стандартизации составов, разработки нормативной базы и подготовки кадров. Авторы предлагают рекомендации по адаптации смесей к климатическим условиям, развитию нормативов и интеграции образовательных программ для ускоренного внедрения технологии и обеспечения качества строительства. Дальнейшие исследования должны сосредоточиться на долговечности напечатанных конструкций и экономической оценке масштабных проектов.*

Ключевые слова: *3D-печать, архитектура, устойчивое строительство, адаптивность, биоразлагаемые материалы, энергоэффективность, цифровое проектирование.*

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CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

During the preparation of this manuscript, the authors used artificial intelligence tools (ChatGPT) solely for editorial assistance, such as improving phrasing and checking grammar, spelling, and punctuation. All ideas, interpretations, and conclusions are the responsibility of the authors, who take full accountability for the content of the article.

АЛҒЫС / ҚАРЖЫЛАНДЫРУ КӨЗІ

Зерттеу жеке қаржыландыру көздерін пайдалана отырып жүргізілді.

МҮДДЕЛЕР ҚАҚТЫҒЫСЫ

Авторлар мүдделер қақтығысы жоқ деп мәлімдейді.

Мақаланы дайындау барысында авторлар жасанды интеллект құралдарын (ChatGPT) тек редакциялық көмек мақсатында пайдаланды: тұжырымдарды жетілдіру, грамматикалық, орфографиялық және тыныс белгілеріндегі қателерді тексеру үшін. Барлық идеялар, интерпретациялар мен қорытындылар авторларға тиесілі, және олар мақаланың мазмұнына толық жауапты.

БЛАГОДАРНОСТИ/ИСТОЧНИК ФИНАНСИРОВАНИЯ

Исследование проводилось с использованием частных источников финансирования.

КОНФЛИКТ ИНТЕРЕСОВ

Авторы заявляют, что конфликта интересов нет.

При подготовке рукописи авторы использовали инструменты искусственного интеллекта (ChatGPT) исключительно для редакторской поддержки: корректировки формулировок, проверки грамматических, орфографических и пунктуационных ошибок. Все идеи, интерпретации и выводы принадлежат авторам, которые несут полную ответственность за содержание статьи.

1 INTRODUCTION

Modern architecture increasingly turns to technologies that are capable not only of shaping new aesthetic solutions but also of responding to the challenges of sustainable development, energy efficiency, and environmental safety. One of the most promising technologies in this field is 3D printing, which in recent years has evolved from an experimental method into a fully-fledged tool of architectural and construction practice. Its advantages are evident: the ability to construct buildings within shorter timeframes, reduce construction waste, employ innovative materials, and create complex forms that are unattainable by conventional construction methods.

The relevance of this study is determined by the need to understand how 3D printing technologies can be integrated into the architectural practice of Kazakhstan, taking into account the country's natural, climatic, and cultural factors.

The aim of the research is to analyze the potential of applying 3D printing and innovative materials in Kazakhstan's construction sector and to identify their role in shaping a sustainable architectural environment.

The scientific novelty of the study lies in a comprehensive approach to examining 3D printing not only as an engineering and technical tool but also as a driver of architectural and cultural transformation. For the first time, the technology is considered in the context of Kazakhstan's climatic conditions and cultural traditions, which makes it possible to propose ways of adapting it and outlining prospects for further development.

2. LITERATURE REVIEW

Research confirms that 3D concrete printing is a well-established process, encompassing digital modeling, mix preparation, and layer-by-layer material deposition **(Gosselin et al., 2016; Buswell et al., 2018)**. Key parameters include rheology, extrusion speed, and interlayer bonding, which influence strength and accuracy **(Wolfs, Bos, & Salet, 2019; Meurer & Classen, 2021)**. Dry mixes and modified cementitious composites with functional additives are actively being developed (Le et al., 2012; Paul et al., 2018). There is growing interest in local materials (clay, earth) and biodegradable composites (PLA, PHAs) to reduce carbon footprint **(Kolesnikova & Alguzhina, 2021; Tkachenko et al., 2025; Pineiro, 2025)**. Projects like Milestone (Netherlands) and Power2Build (Angola) demonstrate the successful application of 3D printing for creating energy-efficient buildings with complex geometries and addressing housing shortages **(Walsh, 2018; Souza, 2021; Frearson, 2018; Pineiro, 2025)**. The experience of BM Partners 3D Print in Kazakhstan confirms the feasibility of constructing earthquake-resistant buildings adapted to local conditions (authors' materials). Digitalization of processes through CAD/BIM/CAM allows for optimized design and production, translating architectural solutions into machine code **(Buswell et al., 2018; Raphael et al., 2022)**. 3D printing offers time and resource savings, as well as environmental benefits through the use of optimized and local materials **(Strohle et al., 2023; Souza, 2021)**. However, barriers exist due to a lack of standards, regulatory frameworks, and data on long-term performance in diverse climatic conditions **(Strohle et al., 2023; Zareiyan & Khoshnevis, 2021)**. For Kazakhstan, relevant research areas include seismic resistance, energy efficiency, adaptation of technologies to local conditions, and the development of national standards **(Le et al., 2012; Strohle et al., 2023)**.

3 MATERIALS AND METHODS

The analysis is based on a comparison of international and Kazakhstani experience in 3D construction, the examination of specific case studies, and the inclusion of data from interviews with developers and project managers of 3D-printed construction projects. In addition, publications and scientific studies on biodegradable composites, energy-efficient poured concretes, and the principles of adaptive design were consulted.

4 RESULTS AND DISCUSSIONS

The Milestone project became the world's first commercial 3D-printed residential development **(Figure 1)**. It comprises five houses, each printed layer by layer from a concrete mix, with the final house intended to be fully assembled on site. The homes exhibit high energy efficiency, complex geometries and an aesthetic that would be impossible to achieve with conventional construction. Thanks to digital control of the construction process and optimized material use, the project achieved a significant reduction in its carbon footprint **(Souza, 2021; Walsh, 2018).**

Figure 1 - The world's first residential project constructed from 3D-printed concrete, Eindhoven, Netherlands. Architects: Houben & Van Mierlo Architecten **(Souza, 2021)**.

In the context of a rapidly expanding housing shortage, particularly in developing countries, 3D printing is increasingly regarded as a tool for accelerated, adaptive and sustainable construction. A notable example is the Angolan innovator Power2Build, which aims to address the country's housing crisis - the company estimates a shortfall of up to 3 million dwellings, concentrated above all in the Luanda metropolitan area, one of the fastest-growing cities in Africa **(Figure 2)**, **(Le, T. T., et al., 2012)**.

Since 2022, Power2Build has been carrying out large-scale housing projects using large-format concrete 3D printing, deploying the Danish company COBOD's BOD2 and BOD3 printer series. These units feature a modular design and are capable of constructing structures up to 15 m high, 15 m wide and 40 m long, with printing speeds of up to 500 mm/s. This approach substantially shortens construction schedules and reduces labor demands by minimizing the need for manual work in masonry and other preparatory on-site operations **(Frearson, A. 2018)**.

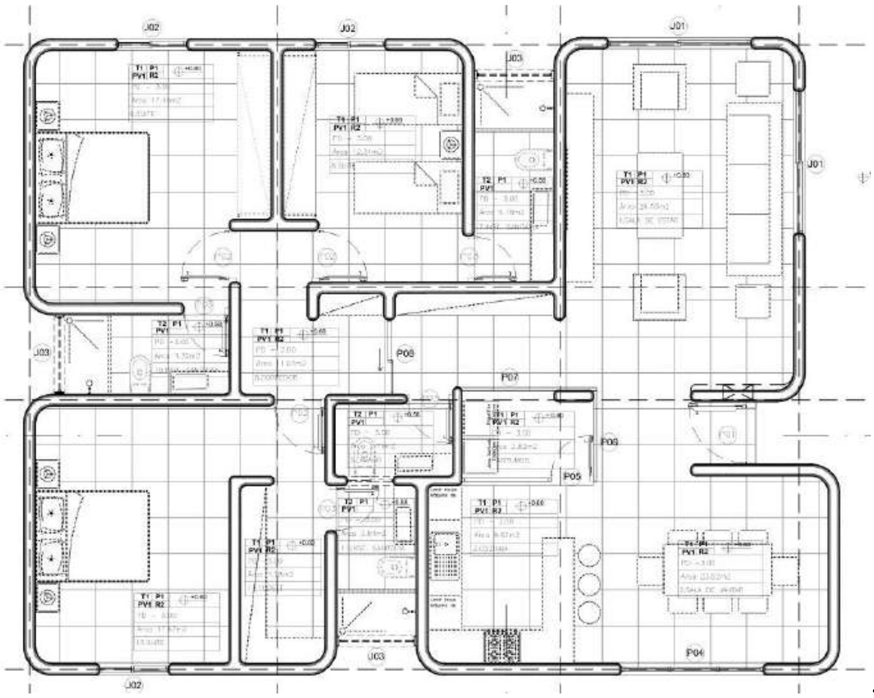

Figure 2 – Architectural plan of a residential duplex project implemented using 3D-printing technology in Angola. Architect: Ilídio Daio, Power2Build **(Frearson, A. 2018)**.

The printing process consists of three stages: modelling, preparation of a construction mix composed of cement, sand, crushed stone and other fillers, and the actual printing **(Figure 3)**. Specialized printers deliver high precision, geometric stability and strong interlayer bonding, in part through the use of continuous tangential material-deposition techniques **(Gosselin et al., 2016; Buswell et al., 2018)**.

The use of locally sourced materials helps reduce the carbon footprint and enhance the sustainability of projects. As part of its continued development, Power2Build plans to introduce clay- and earth-based mixes as well as modular construction solutions for social housing - an approach that makes this experience particularly relevant for resource-constrained regions **(Pineiro, A. 2025)**.

Figure 3 – Construction process of the residential duplex implemented using 3D-printing technology in Angola. Architect: Ilídio Daio, Power2Build **(Pineiro, A. 2025)**.

The Angolan experience demonstrates the potential of adaptive construction at the scale of mass housing, highlighting its relevance not only in high-tech contexts but also for social architecture. Such cases can be instructive when assessing the feasibility of implementing similar approaches in Kazakhstan's architectural practice, taking into account the country's climatic and infrastructural realities. BM Partners 3D Print executed the first residential building in Central Asia constructed with a COBOD BOD2 3D printer **(Figure 4)**. The project was adapted to seismic conditions of up to 7 on the Richter scale. The overall construction process took less than two months, while the wall printing itself lasted only five days. The company is also developing proprietary mix formulations that account for local climatic specifics.

Figure 4 – The first residential building in Central Asia constructed with a COBOD BOD2 3D printer. Architect/Builder: BM Partners 3D Print (authors' material).

Contemporary studies point to the promise of employing biodegradable composites-such as poly (lactic acid) (PLA), polyhydroxyalkanoates (PHAs) and polycaprolactone (PCL)-in architectural applications. These materials demonstrate favorable thermal and mechanical properties, align with environmental standards, and facilitate the integration of circular-economy principles. Their use enables the development of sustainable architectural solutions with minimal environmental impact **(Tkachenko T., et al., 2025)**.

Specialized dry building mixes, optimized for extrusion-based application, are used in construction 3D printing. Their formulation typically comprises a modified cementitious composite with functional additives, reinforcing fibers, and hydrophobizing and frost-resistant agents. The material's rheological properties-particularly its plasticity and setting rate-are of primary importance **(Kolesnikova & Alguzhina, 2021)**.

The adoption of 3D printing in Kazakhstan's architectural practice opens up opportunities to address the housing shortage, especially in remote and seismically active regions. The combination of digital design, novel construction materials and adaptive principles enables the creation of architecture that responds to contemporary challenges - from climatic threats to requirements for energy efficiency and local identity.

The architectural expressiveness afforded by construction 3D printing opens fundamentally new horizons in form-making. The technology allows the erection of spatial volumes with complex geometries while bypassing traditional constraints linked to formwork and manual labor. This expands the creative palette available to architects and designers, making it possible to realize previously unattainable compositional solutions with minimal time and material expenditures **(Strohle, M., et al., 2025)**.

Alongside this, the technology demonstrates high economic efficiency. Shorter construction schedules are accompanied by reduced operating costs through the use of multilayer assemblies with integrated thermal insulation and by optimizing the thermal performance of the building envelope. In some cases, final finishing stages can be partly omitted thanks to the high dimensional accuracy and surface uniformity achieved by printing.

Digitalization of the design and construction process is an integral component of the technology. The application of building information modeling (BIM), parametric design and CAM technologies enables a shift from empirical design to controlled, quantified and resource-optimized solutions. This is particularly relevant for Kazakhstan, where climatic diversity, territorial remoteness and the need for scalable approaches present pressing design challenges.

The digital model is developed in CAD environments (AutoCAD, ArchiCAD, Revit); thereafter the architectural data are adapted for printing in specialized CAM programs, such as Rhino with the Grasshopper module or the proprietary interfaces provided by 3D-printer manufacturers. The final stage is the generation of the machine control code (G-code), which the printing system executes to realize the object's geometry in the chosen material.

5 CONCLUSIONS

The conducted analysis indicates that 3D printing in architecture has transitioned from an experimental technology to a practical tool capable of addressing sustainable-construction tasks. Accordingly, we arrive at the following conclusions:

1. 3D printing in architecture has moved out of the experimental domain and is now a practical instrument ready for deployment in construction.
2. International and Kazakhstani examples (the Milestone project, Power2Build, and the BM Partners 3D Print residential building in Almaty) confirm the technology's potential for rapid and resource-efficient building delivery.
3. For Kazakhstan, the adoption of 3D printing is particularly relevant given seismicity, climatic heterogeneity and the need to modernize the housing stock.
4. The use of locally sourced materials, modified concretes and biodegradable composites, combined with digital design methods, enables the creation of adaptive and energy-efficient architectural solutions.
5. Form-making freedom, material savings and the integration of BIM/CAM systems reinforce the competitive advantages of 3D printing within the construction industry.

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REVIEW ARTICLE

MODERNIZATION OF RESIDENTIAL MICRODISTRICTS THROUGH THE INTEGRATION OF ECO-AGRO-ARCHITECTURAL ELEMENTS

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Abstract. *Modern residential microdistricts in post-Soviet cities are characterized by building wear, a shortage of public spaces, high thermal loads, and an unstable water regime. The integration of eco-agro-architecture elements-courtyard vegetable gardens and orchards, green roofs, rooftop greenhouses, vertical farms, and nature-based stormwater infrastructure-is considered an engineering-architectural solution that combines climate adaptation, increased energy efficiency, and improvement of urban environmental quality. The aim of this study is to substantiate engineering-architectural approaches to the modernization of post-Soviet residential microdistricts through the integration of eco-agro-architecture elements and to determine the conditions for their effective and safe implementation in Kazakhstan. The research methodology includes a qualitative comparative analysis of "green" infrastructure solutions as well as a synthesis of design principles and a phased implementation model. The study results are presented as a three-step model-quick measures on existing roofs and courtyards; pilots on public buildings with monitoring of energy use and water drainage; scaling through municipal programs and standards. The practical significance lies in reducing peak stormwater runoff, mitigating thermal loads, and increasing the resource efficiency of buildings, as well as in forming social practices for the shared use of courtyard and rooftop spaces. The results are intended for akimats, designers, and management organizations and can be applied when preparing modernization passports and developing pilot projects.*

Keywords: *eco-agro architecture; urban agriculture; green roofs; rooftop greenhouses; vertical farms; microdistrict modernization.*

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ШОЛУ МАҚАЛАСЫ

ЭКОАГРОАРХИТЕКТУРА ЭЛЕМЕНТТЕРІН ИНТЕГРАЦИЯЛАУ АРҚЫЛЫ ТҰРҒЫН ШАҒЫНАУДАНДАРДЫ ЖАҢҒЫРТУ

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Аңдатпа. *Посткеңестік қалалардың заманауи тұрғын шағын аудандары ғимараттардың тозуы, қоғамдық кеңістіктер тапшылығы, жылулық жүктеменің жоғары болуы және су режимінің тұрақсыздығымен сипатталады. Экоагроархитектура элементтерін - аула бағалары мен бақтарын, жасыл шатырларды, шатыр жылыжайларын, тік агрофермаларды және табиғатқа ұқсас нөсерлік инфрақұрылымды - интеграциялау климатқа бейімделуді, энерготиімділікті арттыруды және қалалық ортаның сапасын көтеруді ұштастыратын инженерлік-сәулеттік шешім ретінде қарастырылады. Осы зерттеудің мақсаты - экоагроархитектура элементтерін интеграциялау арқылы посткеңестік тұрғын шағынаудандарды жаңғыртудың инженерлік-сәулеттік тәсілдерін негіздеу және оларды Қазақстанда тиімді әрі қауіпсіз енгізудің шарттарын айқындау. Әдістеме «жасыл» инфрақұрылым шешімдерінің сапалық салыстырмалы талдауын, сондай-ақ жобалау қағидаттары мен кезең-кезеңімен енгізу моделін синтездеуді қамтиды. Нәтижелер үшсатылы модель түрінде ұсынылған: бар шатырлар мен аулаларда жедел шаралар; энергия тұтынуы мен су бұрудың мониторингі бар қоғамдық ғимараттардағы пилоттар; қалалық бағдарламалар мен стандарттар арқылы ауқымдау. Типтік шешімдер үшін жүктемелер мен пайдалану талаптары бойынша бағдарлық мәндер келтірілді. Практикалық маңыздылығы - нөсерлік ағынның шоғырланған шыңдарын төмендету, жылулық жүктемені жұмсарту және ғимараттардың ресурс тиімділігін арттыру, сондай-ақ аулалық және шатырлық кеңістіктерді ортақ пайдалану бойынша әлеуметтік тәжірибелерді қалыптастыру. Нәтижелер әкімдіктерге, жобалаушыларға және басқарушы ұйымдарға арналған және жаңғырту паспорттарын дайындау мен пилоттық жобаларды әзірлеуде қолданылуы мүмкін.*

Түйін сөздер: *экоагроархитектура; қалалық ауыл шаруашылығы; жасыл шатырлар; шатыр жылыжайлары; тік агрофермалар; шағынаудандарды жаңғырту.*

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ОБЗОРНАЯ СТАТЬЯ

МОДЕРНИЗАЦИЯ ЖИЛЫХ МИКРОРАЙОНОВ С ИНТЕГРАЦИЕЙ ЭЛЕМЕНТОВ ЭКОАГРОАРХИТЕКТУРЫ

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Аннотация. *Современные жилые микрорайоны постсоветских городов характеризуются износом зданий, дефицитом общественных пространств, высокой тепловой нагрузкой и нестабильным водным режимом. Интеграция элементов экоагроархитектуры - дворовых огородов и садов, зелёных крыш, крышных теплиц, вертикальных ферм и природоподобной ливневой инфраструктуры - рассматривается как инженерно-архитектурное решение, совмещающее климатическую адаптацию, рост энергоэффективности и повышение качества городской среды. Целью данного исследования является обоснование инженерно-архитектурных подходов к модернизации постсоветских жилых микрорайонов путём интеграции элементов экоагроархитектуры и определение условия их эффективного и безопасного внедрения в Казахстане. Методология исследования включает качественный сравнительный анализ решений «зелёной» инфраструктуры, а также синтез проектных принципов и поэтапной модели внедрения. Результаты исследования представлены в виде сформированой трёхшаговой модели - быстрые меры на существующих кровлях и дворах; пилоты на общественных зданиях с мониторингом энергопотребления и водоотведения; масштабирование через городские программы и стандарты. Практическая значимость состоит в снижении пиков ливневого стока, смягчении тепловой нагрузки и повышении ресурсной эффективности зданий, а также в формировании социальных практик совместного использования дворовых и кровельных пространств. Результаты адресованы акиматам, проектировщикам и управляющим организациям и могут применяться при подготовке паспортов модернизации и разработке пилотных проектов.*

Ключевые слова: *экоагроархитектура; городское сельское хозяйство; зелёные крыши; крышные теплицы; вертикальные фермы; модернизация микрорайонов.*

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CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

During the preparation of this manuscript, the authors used artificial intelligence tools (ChatGPT) solely for editorial assistance, such as improving phrasing and checking grammar, spelling, and punctuation. All ideas, interpretations, and conclusions are the responsibility of the authors, who take full accountability for the content of the article.

АЛҒЫС / ҚАРЖЫЛАНДЫРУ КӨЗІ

Зерттеу жеке қаржыландыру көздерін пайдалана отырып жүргізілді.

МҮДДЕЛЕР ҚАҚТЫҒЫСЫ

Авторлар мүдделер қақтығысы жоқ деп мәлімдейді.

Мақаланы дайындау барысында авторлар жасанды интеллект құралдарын (ChatGPT) тек редакциялық көмек мақсатында пайдаланды: тұжырымдарды жетілдіру, грамматикалық, орфографиялық және тыныс белгілеріндегі қателерді тексеру үшін. Барлық идеялар, интерпретациялар мен қорытындылар авторларға тиесілі, және олар мақаланың мазмұнына толық жауапты.

БЛАГОДАРНОСТИ/ИСТОЧНИК ФИНАНСИРОВАНИЯ

Исследование проводилось с использованием частных источников финансирования.

КОНФЛИКТ ИНТЕРЕСОВ

Авторы заявляют, что конфликта интересов нет.

При подготовке рукописи авторы использовали инструменты искусственного интеллекта (ChatGPT) исключительно для редакторской поддержки: корректировки формулировок, проверки грамматических, орфографических и пунктуационных ошибок. Все идеи, интерпретации и выводы принадлежат авторам, которые несут полную ответственность за содержание статьи.

1 INTRODUCTION

Residential districts formed during the Soviet and post-Soviet periods played a key role in providing affordable housing and shaping the urban structure. Their architectural and planning model was based on standardization and utilitarianism: typical panel and brick apartment blocks, a minimal set of social facilities and green areas, and a rigid functional hierarchy. This system made it possible to address the housing shortage of its time efficiently, yet under contemporary conditions its significant limitations have become evident.

A large share of the housing stock has now been in operation for more than 40-50 years, leading to structural deterioration, obsolescence of engineering systems, and reduced energy efficiency. Equally evident is the moral and functional obsolescence of planning solutions: standardized apartments and courtyard spaces no longer meet current demands for quality of life, functional diversity, and social expectations of urban residents.

An additional challenge is the shortage of public and recreational areas. Spaces originally designed as utilitarian or transit zones do little to stimulate resident interaction and fail to create conditions for local community building. The underdevelopment of ecological infrastructure further exacerbates the situation: systems for waste separation and recycling, rational water use, and energy conservation were either not envisaged or remain fragmented. This reinforces the social alienation typical of standardized environments, where people often remain anonymous users of space and feel neither attachment to nor responsibility for it.

The combination of these factors makes the modernization of residential districts one of the priority tasks of contemporary urban development. Importantly, this process cannot be reduced to building refurbishment or cosmetic landscaping. A comprehensive approach is required, one that reinterprets the residential district not merely as a place of dwelling but as a fully-fledged socio-ecological unit of the city-adaptive to new challenges, resilient in operation, and capable of ensuring high urban environmental quality.

The microdistrict model of development provided mass housing and basic infrastructure, yet today it requires profound modernization. The physical deterioration of envelopes and engineering systems, the obsolescence of courtyards, low energy efficiency, and climate vulnerability necessitate integrated solutions. Traditional measures (major repair, “cosmetic” landscaping) often fail to deliver sustainable improvements in quality of life. The integration of productive green solutions-eco-agroarchitectural elements-makes it possible to view the building and courtyard as a unified socio-ecological system with partially closed loops of energy, water, and materials.

This includes courtyard gardens and orchards, green roofs (extensive/intensive), rooftop greenhouses and vertical farms, as well as nature-based stormwater infrastructure (rain gardens, bioswales, rainwater harvesting). Such measures simultaneously improve the microclimate, reduce stormwater runoff, support biodiversity, and create new scenarios for the use of shared spaces. The social impact is reflected in the development of local communities, co-governance, and environmental education.

The present study systematizes international experience and scientific evidence, highlights engineering-ecological effects, organizational requirements and constraints, and proposes a phased implementation model for the context of Kazakhstan, oriented toward pilot projects, monitoring, and subsequent scaling up.

Residential districts of the Soviet and post-Soviet period in Kazakhstan are characterized by physical and functional obsolescence, low energy efficiency, and vulnerability to climatic and hydrological impacts. Traditional measures (capital repairs, cosmetic landscaping) deliver only limited and short-term improvements. Under these conditions, the integration of eco-agroarchitectural elements-green roofs (extensive and intensive), rooftop greenhouses, vertical farms, and nature-based stormwater infrastructure is considered a multifunctional strategy that simultaneously reduces peak stormwater runoff, mitigates urban overheating, increases the resource efficiency of buildings, and enhances resident engagement.

The scientific problem lies in the absence, within the Kazakhstani context, of systematized engineering and architectural principles and regulations for implementing such solutions, accounting for local snow, wind, and seismic loads, water and energy management, selection of resilient species, sanitation, operation, and co-governance models.

The aim of the study is to substantiate approaches to the modernization of residential districts through the integration of eco-agroarchitectural elements and to define the conditions for their effective and safe implementation in Kazakhstan.

To achieve this aim, the following objectives are addressed:

−to conduct a qualitative comparative analysis of typical interventions using a unified parameter matrix;

−to synthesize design principles and operational regulations;

−to propose a phased model (“quick measures - pilot projects - scaling up”) supported by target monitoring metrics;

−to refine load benchmarks and safety requirements.

A brief review of contemporary literature shows that green roofs and related solutions provide energy, hydrological, and ecosystem benefits when properly adapted to climate-specific construction and maintenance requirements, while integrated greenhouses and vertical farms demonstrate the potential for resource synergies between buildings and agro-systems. The success of implementation is determined by regulatory support, operational discipline, and resident participation.

2 LITERATURE REVIEW

Green roofs are considered a multifunctional ecosystem technology that combines climate adaptation with improvements to urban environmental quality. Studies by Oberndorfer, Lundholm, Bass, Mentens, Raes, Hermy **(Oberndorfer, Lundholm, Bass et al., 2007; Mentens, Raes & Hermy, 2006)** demonstrate in detail that the structure of the roof layers and the selection of vegetation determine the range of ecosystem services-from reducing peak stormwater runoff to mitigating the urban heat island effect in metropolitan areas.

The energy effect of green roofs is manifested in the reduction of summer heat gains and the lowering of building cooling loads. For accurate evaluation, researchers emphasize the need to calibrate numerical models with data from in-situ measurements on real buildings across different climatic regimes **(Jaffal, Ouldboukhitine & Belarbi, 2012)**.

The hydrological efficiency and long-term performance of green roofs depend on design and operational parameters. Reviews by Susca, Li, Babcock **(Susca, 2019; Li & Babcock, 2014)** systematize the influence of substrate depth and properties, drainage solutions, and maintenance regimes on stormwater retention and detention, including seasonal variability.

The biological composition of green roof systems requires conscious selection of plant species suited to specific climatic conditions and operational objectives. Research has shown that the resilience of plant communities and their contribution to microclimatic effects depend on diversity, life forms, and stress tolerance of species, as well as on maintenance strategies **(Shafique, Kim & Rafiq, 2018; Dvorak & Volder, 2010)**.

Rooftop urban agriculture confirms the practical feasibility of combining the technological and food-producing functions of rooftops. Whittinghill, Rowe, and Sanye-Mengual, Oliver-Sola, Montero, Rieradevall **(Whittinghill & Rowe, 2012; Sanye-Mengual, Oliver-Sola, Montero & Rieradevall, 2015)** describe requirements for sanitation, logistics, and product quality, and assess the environmental and economic consequences of integrating agricultural practices into the urban fabric using life-cycle assessment methods.

Building-integrated rooftop greenhouses (BIRG/I-RTG) utilize the exchange of heat and moisture between heated indoor spaces and the greenhouse volume. Several studies **(Sanjuan-Delmas, Rovira-Val, Nadal, Rieradevall & Josa, 2018; Nadal, Ceron-Palma, Cuerva et al., 2017)** demonstrate the potential for heat recovery, utilization of CO_2 from ventilation, and rainwater harvesting, which improve the energy performance and environmental profile of urban food production.

The organizational dimension of such projects requires cross-sectoral collaboration among municipalities, businesses, and residents. Research by Benis, Reinhart, Ferrao, and Specht, Siebert, Hartmann et al., **(Benis, Reinhart & Ferrao, 2018; Specht, Siebert, Hartmann et al., 2014)** emphasizes the importance of stakeholder mapping, early-stage communication, and overcoming institutional barriers-from rooftop access regulations to operational regimes and insurance requirements.

A systematic review of rooftop urban agriculture highlights typologies, governance models, and key barriers to implementation Kalantari, Tahir, Joni, Fatemi **(Kalantari, Tahir, Joni & Fatemi, 2018)**. It is noted that successful scaling depends on municipal support programs, standards, and cooperative forms of resident participation.

Vertical farming is evolving at the intersection of agricultural technology, microclimate engineering, and digital control. Studies by Al-Kodmany, and Beacham, Vickers, Monaghan 2019 **(Al-Kodmany, 2018; Beacham, Vickers & Monaghan, 2019)** underline the sensitivity of project economics to energy efficiency, tariffs, and the quality of thermal integration, as well as the importance of modular design.

LED-based horticultural lighting has become a key driver of productivity in controlled environments. Spectral tuning and dosing strategies allow optimization of photosynthesis and product quality while reducing specific energy consumption, as comprehensively reviewed by Pattison, Tsao, Brainard, Bugbee **(Pattison, Tsao, Brainard & Bugbee, 2018).**

Assessments of the food production potential of cities indicate that a significant share of vegetable output can be localized, provided that climate, building morphology, and sanitary-hygienic standards are properly considered. Such assessments are useful for scenario planning of urban food systems and logistics **(Payen, 2022).**

The ecological effects of green roofs include reductions in air and water pollution, as well as the filtration of dust and particulates **(Rowe, 2011; Van Mechelen, Dutoit & Hermy, 2015)**. At the same time, plant selection and the development of monitoring metrics for vegetation quality have a critical influence on the resilience of ecosystem services and the long-term performance of these systems.

The concept of “reconciliation ecology” applied to rooftops and walls emphasizes the compatibility of urban development with biodiversity. Operational reports underline the necessity of scheduled maintenance and condition monitoring, while long-term observation series are documented in studies by Francis, Lorimer, Liu, Minor **(Francis & Lorimer, 2011 and Liu & Minor, 2005).**

Empirical data confirm the contribution of green roofs to maintaining and enriching urban biodiversity **(Williams, Lundholm & MacIvor, 2014; Roehr & Kong, 2010)**. Parallel findings show a substantial reduction of surface runoff in temperate climates when design and operational requirements are met.

Extensive green roofs in several cities have demonstrated reductions in energy consumption and improvements in indoor thermal comfort. In addition, attenuation of the urban heat island effect has been recorded at the neighborhood and microclimate levels **(Getter & Rowe, 2006; Alvarez & Velasco, 2020).**

Regional research within the post-Soviet context, including case studies in Almaty, highlights the importance of regulatory support and the inclusion of green solutions in modernization roadmaps. The influence of renovation governance regimes on the success of green infrastructure implementation is discussed in comparative works by Murzabayeva, Lapshina, Tuyakayeva, and Khmelnitskaya, Ihalainen, **(Murzabayeva, Lapshina & Tuyakayeva, 2022; Khmelnitskaya & Ihalainen, 2021).**

Design recommendations for rooftop agriculture establish requirements for access, safety, and operation, including rainwater harvesting and the management of organic waste. Long-term observations of rooftop vegetation clarify successional trajectories, resilience, and maintenance volumes **(Daneshyar, 2024; Kohler, 2006).**

Socioeconomic assessments demonstrate that when externalities are accounted for (microclimate, runoff, health, community effects), the benefits of green roofs increase significantly **(Bianchini & Hewage, 2012; Lundholm, 2006)**. The "habitat template" approach provides a framework for linking architecture and biodiversity, setting design guidelines for façades and rooftops.

3 MATERIALS AND METHODS

The comparative method involved a qualitative analysis of typical interventions-extensive and intensive green roofs, rooftop greenhouses, vertical farms, and nature-based stormwater infrastructure-using a unified parameter matrix. The parameters included:

−Design loads and verification of load-bearing capacity (including snow, wind, and seismic actions);

−Structural nodes and detailing;

−Water and energy management (rainwater harvesting, heat recovery/utilization);

−Operational and maintenance requirements;

−Sanitation and safety standards;

−Indicative CAPEX/OPEX values, where available.

Based on the resulting intervention profiles, a synthesis of design principles and a phased implementation model was developed, tailored to the conditions of residential district modernization.

3.1 Main directions of modernization

The modernization of residential districts implies a comprehensive set of transformations that affect not only the architectural and spatial organization of development but also its engineering, environmental, and social dimensions. One of the priority directions is the renewal of the housing stock: façade reconstruction, thermal insulation of building envelopes, replacement of outdated engineering networks, and the implementation of modern energy-efficient technologies. These measures can significantly reduce operating costs, improve comfort levels, and extend the service life of buildings.

It is also important to reconsider attics, basements, and technical floors, which previously served exclusively utilitarian purposes: they may be adapted for household and public functions, cultural venues, and educational spaces.

Equally important is the creation of new public and recreational areas. Courtyard territories, once perceived as secondary or transit spaces, acquire multifunctional roles during modernization: they become places for recreation, sports, cultural activities, and resident interaction. Such transformation redefines the district from a collection of individual buildings into a cohesive social space that strengthens horizontal connections and fosters local identity.

Special attention is given to environmental aspects. In modern cities, modernization is impossible without systems for rational water use, waste separation and recycling, the application of renewable energy sources, and the enhancement of ecological resilience in urban development. Architectural and engineering solutions must be integrated into a single concept in which buildings and courtyards function as interconnected elements of a unified environment.

Ultimately, the modernization of residential districts becomes a tool for shaping a qualitatively new urban environment, where architectural, engineering, and social transformations reinforce one another and are directed toward creating a sustainable, comfortable, and adaptive living space.

3.2 Integration of eco-agroarchitecture into modernization processes

A key principle of such transformation is multifunctionality. Spaces previously regarded as purely utilitari

an or secondary (courtyards, passage zones, parking areas) can be reimagined as places for shared living and activity. Here, gardening communities may emerge: residents cultivate greens, organize workshops, host lectures, festivals, and neighborhood gatherings. The user becomes a co-author of the environment, which increases engagement and responsibility, strengthens horizontal ties, and supports local identity.

In conditions of dense urban development and a shortage of available land, the importance of vertical greening and green roofs grows considerably. These solutions compensate for land scarcity, provide additional recreational areas, and deliver a wide range of benefits: reducing air and noise pollution, improving building insulation, and contributing to energy savings. When integrated with systems for rainwater harvesting, organic waste recycling, and smart sensor technologies, green roofs and façades become elements of closed ecological cycles: each building functions as a miniature "living organism" embedded within the microdistrict system.

Small-scale agricultural production represents another essential component. International experience demonstrates that urban food cultivation is both possible and effective, offering significant educational and therapeutic potential. Under contemporary conditions, such practices evolve through rooftop and basement greenhouses, modular farms, micro-facilities for organic waste processing, and compost production. These facilities may operate as community initiatives, cooperatives, or social enterprises, simultaneously stimulating the local economy, creating jobs, and reducing dependence on external food supplies.

Particular attention is also given to ecological water infrastructure. Traditional engineering solutions for stormwater drainage are gradually giving way to nature-based systems: rain gardens, bio-ponds, and water-retentive landscape forms. These reduce the load on urban sewer systems, prevent localized flooding, and create aesthetically appealing and comfortable recreational spaces. In the context of climate change and increasingly frequent extreme precipitation events, such solutions become critically important, shaping a resilient system of interaction between the urban fabric and natural processes.

A significant direction is the architectural adaptation of existing buildings. Attics, technical floors, and other "dead zones" can be converted into greenhouses, conservatories, co-working spaces, or cultural pavilions, thereby activating previously unused areas. The addition of photovoltaic panels, rainwater harvesting systems, composters, and household waste processing units renders buildings partially autonomous and resource-efficient, reducing operating costs and enhancing the resilience of the urban environment.

New practices require not only engineering but also cultural change. Programs of "green education" are essential for raising environmental literacy, developing skills in gardening and sustainable consumption. Resident engagement through educational initiatives, joint projects, and volunteering not only broadens knowledge but also fosters a responsible attitude toward the environment, laying the foundation for long-term transformation of urban lifestyles.

Thus, the eco-agroarchitectural approach spans all levels of the urban environment-from individual courtyards and buildings to entire blocks. Its implementation reduces ecological pressures, strengthens climate resilience, develops social connections, and supports the local economy. Importantly, this is not merely a technical modernization, but a large-scale socio-cultural process in which every resident plays an active role: the city of the future is born from the synergy of engineering solutions and collective efforts striving for harmony between people and nature.

3.3 Case example

Havana (Cuba). The urban organopónicos system, covering areas of up to several hectares across sites of varying scale, emerged during a food crisis and demonstrated the effectiveness of utilizing vacant land-along streets, on rooftops, and in courtyards-for organic vegetable cultivation with minimal resource inputs **(Figure 1)**. By 1998, Havana hosted more than 8,000 urban farms, supplying a substantial share of the residents' vegetable.

Figure 1 - Rows of the “Organopónico Plaza” area with seasonal greens: lettuce, spring onion, and others **(Cuba's organic revolution, 2008)**

Bosco Verticale (Milan, Italy). A residential complex with vertical façade greening: more than 90 plant species, including trees and shrubs, integrated into the architecture to enhance biodiversity and microclimate **(Figure 2)**.

Figure 2 - Greened loggias of Stefano Boeri’s iconic building Bosco Verticale. **(Boeri Studio's Bosco Verticale was the most significant building of 2014, 2025)**

One Central Park (Sydney, Australia). A multifunctional building developed as part of the Central Park redevelopment project. The skyscraper features a “hanging garden” façade, LED illumination, and an integrated irrigation system within the framework of sustainable architecture. It was recognized as one of the world’s best high-rise residential complexes in 2014. At 116 meters in height, the building’s façades present challenging conditions for vegetation due to strong winds and intense solar radiation (despite its orientation away from the south). For this reason, 350 plant species capable of withstanding such stresses were selected for greening. Irrigation is supplied by the complex’s wastewater, treated on-site through its own filtration system **(Figure 3)**.

Figure 3 - Terrace of the residential complex planted with vegetation. **(N.Frolova, 2014)**

Lufa Farms (Montreal, Canada). Commercial greenhouses located on the rooftops of industrial buildings, supplying the city's population with fresh vegetables while minimizing logistics and enhancing food system resilience **(Figure 4).**

Figure 4 - The largest greenhouse located on the rooftop of Lufa Farms' wholesale distribution center **(Top 5 largest greenhouses in the world, 2024**)

Figure 5 diagram classifying solutions: courtyard gardens/orchards, green roofs (extensive/intensive), rooftop greenhouses, vertical farms, and nature-based stormwater infrastructure. For each typology, the diagram illustrates placement zones and key construction details (root-resistant waterproofing, drainage and filter layers, structural frames/anchoring, water supply and access points). Minimum requirements for engineering interfaces (irrigation, drainage, power supply) and load limitations are indicated. The scheme is intended to support the selection of configurations according to the baseline conditions of a given site.

Figure 5 - Typologies of eco-agroarchitectural element integration (authors' material)

Figure 6 - Three-phase model: quick interventions on existing roofs/courtyards; pilot projects on public buildings with baseline monitoring; and scaling-up based on standards and programs. For each phase, the inputs (structural assessment, utilities), target metrics (runoff retention, ΔT, energy consumption), and decision points are indicated. The structure of the phases is aligned with scheduling, resources, and management risks.

Figure 6 - Phased model for implementing solutions in residential districts (authors' material)

Table 1 presents additional permanent loads, indicative capital and operating expenditures, as well as expected effects and constraints for each type of solution. For green roofs, load benchmarks are given in the water-saturated state: extensive ~ 0.6-1.2 kN/m^2, intensive ≥1.5 kN/m^2; for rooftop greenhouses, the self-weight of glazing/structural frames together with wind and snow actions are considered; for vertical farms, the weight of equipment and water is taken into account.

The consolidated indicators are intended for pre-design structural capacity checks, preliminary selection of construction solutions, and high-level budgeting (CAPEX/OPEX). At the same time, operational constraints (access, sanitary requirements, energy demand) are recorded, to be further detailed at the project documentation stage.

Table 1
Comparison of Solutions by Loads, Costs, and Characteristics (author's material)

Solution	Additional Load	Capital Expenditures	Operating Expenditures	Key Effects	Constraints
Courtyard Gardens	Low	Low	Low	Community building, educational effect, local microclimate improvement	Need for plot management and water supply
Extensive Green Roof	0.6-1.2 kN/m² (saturated condition)	Low-Medium	Low	Reduction of surface runoff, mitigation of overheating, increase in biodiversity	Maintenance of substrate and drainage elements
Intensive Green Roof	≥ 1.5 kN/m²	Medium-High	Medium	Food production, climatic and recreational benefits	Requirements for load-bearing structures and irrigation system
Building-Integrated Rooftop Greenhouse (BIRG)	Medium (weight of frame and glazing)	High	Medium-High	Food production, integration of closed resource cycles	Increased energy demand, sanitary requirements
Vertical Farm	Low-Medium (equipment and water weight)	High	High	High yield and year-round production	Increased energy demand, need for specialized expertise

Table 2 systematizes elements of nature-based water infrastructure (rain garden, bioswale, rainwater storage tank, composting, and PV-green roof combination), indicating their target functions, maintenance requirements, and typical locations.

Operational regimes include periodic removal of sediment, inspection of filters and overflows, checks of pumping equipment, and seasonal care of vegetation. The information provided defines the composition of the stormwater management chain and the operational practices required to ensure the designed hydraulic efficiency.

A unified parameter format ensures comparability of alternatives when developing operation and maintenance regulations.

Table 2
Elements of Water Infrastructure and Maintenance Requirements (author's material)

Intervention	Maintenance	Typical Locations
Rain Garden	Seasonal plant care, removal of sediment	Courtyard spaces
Bioretention System (Bioswale / Biofilter)	Regular removal of debris and sediment, inspection of inlets/outlets	Edges of pedestrian paths and parking areas
Rainwater Harvesting Tank	Filter and pump maintenance, tank flushing	Rooftop or basement areas
Composting	Periodic aeration and mixing, moisture control	Courtyards and service areas
Photovoltaic Panels Combined with Green Roof	Regular cleaning and monitoring of panels and vegetation layer	Accessible/operated rooftops

4 RESULTS AND DISCUSSION

The challenge of modernizing residential districts today extends far beyond engineering and technical solutions. Contemporary cities face environmental, social, and food-security pressures, and only comprehensive approaches can deliver durable outcomes. Integrating eco-agroarchitectural elements into residential environments appears to be a promising direction that simultaneously enhances the quality of urban infrastructure and creates new opportunities for residents.

Although Kazakhstan currently lacks examples of the systematic integration of agro-ecological solutions into microdistrict development, international practice demonstrates successful models of urban agriculture: rooftop greenhouses and farms, vertical farms, and community agro-spaces have been implemented and operate stably in major metropolitan areas. Moreover, academic studies and peer-reviewed publications offer methodological guidance for designing such systems in residential settings, forming a basis for adaptation to the Kazakhstani context.

Thus, the modernization of residential districts with the integration of eco-agroarchitectural elements can become one of the key directions in the development of Kazakhstan's urban environment. This approach would not only improve the energy performance and environmental quality of the housing stock, but also foster new forms of social activity, strengthen local food security, and move cities closer to a sustainable development model. The absence of domestic precedents should not be viewed as a constraint; on the contrary, it opens opportunities for pioneering projects capable of setting new standards for the design and operation of the residential microdistricts of the future.

The analysis of sources confirms that combining green roofs with nature-based stormwater infrastructure consistently reduces both total volumes and peak stormwater flows, while simultaneously improving the microclimate through evaporative cooling and increased thermal inertia of the building envelope. These measures help mitigate the urban heat-island effect and, with appropriate substrate and plant selection, enhance the structural and species diversity of urban biotopes. For durable outcomes, not only the types of interventions matter, but also their coordination: rain gardens, bioretention systems, rainwater storage, composting, and green roofs must operate as a unified courtyard- and block-scale ecosystem.

The hydrological effect manifests through two mechanisms: retention and detention. Green roofs and rain gardens "cut" peak runoff by redistributing flows over time, thereby reducing loads on existing storm sewers and lowering the likelihood of courtyard flooding. Biologically based stormwater systems (bioswales, biofilters) improve water quality via filtration through vegetative and mineral layers and promote infiltration where geotechnical conditions allow. Rainwater tanks enable partial capture of precipitation for subsequent irrigation, reducing potable-water demand and stabilizing vegetation water regimes during dry periods. The effectiveness of these measures depends on proper hydrologic siting within courtyard topography, the specified share of pervious surfaces, and the overflow capacity during peak rainfall.

The microclimatic effect is expressed in lower surface temperatures of roofs and pavements due to evaporation and shading, which improves pedestrian-level thermal comfort and decreases building cooling loads in warm seasons. Green roofs additionally shield roofing assemblies from extreme temperature swings and ultraviolet exposure, extending the service life of waterproofing. At the block scale, a mosaic approach is important: alternating green elements with pervious coverings and tree-shrub groupings creates heat-resilient micro-zones and improves the aeration of courtyard spaces.

Biodiversity support is achieved through careful selection of substrate and plant species. Practice shows that the use of native and drought-tolerant species reduces irrigation demand, increases stress resistance, and promotes the formation of stable trophic networks (pollinators, entomofauna, urban birds). Gradual development is important: first establishing a resilient baseline floristic composition, then introducing continuous-bloom flowerbeds and "pockets" with seed-bearing plants to enable natural self-seeding. At the same time, invasive species must be excluded, and allergenicity requirements must be considered.

4.1 Productive solutions

Rooftop greenhouses and vertical farms-add new value but impose higher requirements on engineering integration. Rooftop greenhouses effectively utilize surplus building heat and solar radiation; with recovery systems, it is possible to stabilize thermal regimes and reduce auxiliary heating costs. Vertical farms typically require precise control of artificial lighting and microclimate, which imposes demands on power supply, heat removal from light sources, and water treatment systems. In both cases, sanitary regulations are mandatory: monitoring water quality for irrigation, maintaining hygienic working conditions, pest management without toxic agents, ensuring adequate ventilation, and preventing condensation that could damage building envelopes. Without these measures, productive systems risk becoming sources of operational problems.

For post-Soviet microdistricts, structural capacity assessment and operational safety are critical. Before implementing a green roof or greenhouse, load-bearing structures must be verified: accounting for permanent loads from water-saturated substrate, snow and wind actions, and dynamic loads from maintenance. Fire-safety measures (fire breaks, fire-service access), safe roof access, and maintenance protocols that avoid damage to waterproofing are essential. At the courtyard scale, existing networks, slopes, and potential internal flooding zones must be considered; bioswales and rain gardens should be placed to avoid soaking building foundations and to ensure safe overflow discharge.

4.2 Operation and maintenance are key determinants of long-term performance.

For green roofs, this includes seasonal servicing of the vegetative layer, inspection of gutters, drains, and gravel firebreaks, and restoration of mulch. For biobased stormwater systems, routine removal of debris and sediment is required, along with inspection of filter layers and re-establishment of turf after extreme rainfall. Rainwater tanks require filter and pump checks, preventive flushing, and water-quality monitoring. Introducing composting closes the organic loop: green waste from courtyards and roofs becomes a resource for substrates and mulch. Effectiveness increases when a responsibility matrix defines the roles of the homeowners' association/management company, landscaping contractors, and active residents, as well as baseline service levels and response times to events (drought, heavy downpour, windthrow).

Co-governance models and resident participation enhance system resilience.

Pilot plots can be assigned to courtyard communities under the guidance of professional curators: residents participate in species selection and conduct simple end-to-end monitoring (e.g., sediment gauges, visual checklists), while the management company handles high-risk professional tasks (pump maintenance, waterproofing repairs). Public displays and digital panels at building entrances that show accumulated rainwater volumes, the number of irrigation events without potable water, and surface-temperature trends make results visible and build trust.

A phased strategy reduces risks and builds datasets for scaling.

Phase 1 (quick wins): low-risk interventions-rain gardens in flow-accumulation zones, localized biofilters along parking edges, small tanks for landscape irrigation.

Phase 2: extensive green roofs on technical areas with easy access and minimal additional weight.

Phase 3: integration of photovoltaic panels with green roofs to improve energy and microclimatic performance.

Phase 4: productive solutions-rooftop greenhouses and compact vertical farms-in buildings with verified structural reserve and ready engineering infrastructure.

Each phase is accompanied by monitoring and iterative refinement of O&M protocols.

Monitoring should be structured as an evidence-based management system. Core indicators include: the proportion of runoff reduced and frequency of overflows, surface temperature of roofs and pavements, substrate moisture, plant survival rates, maintenance costs, and number of complaints. Additional indicators may cover biodiversity (pollinator and bird counts), while for productive systems they include yield and specific energy intensity. Data collected over at least one full hydrological year enables adjustments to design solutions, optimization of maintenance schedules, and evidence-based scaling of successful prototypes to adjacent courtyards and rooftops.

The economic dimension consists of initial capital investments and operating expenditures. Operating costs can be reduced through deliberate selection of durable materials, standardization of details, and training of staff and residents in simple maintenance protocols. Additional value is created by the "stacking of effects": water savings from storage tanks, reduced cooling costs, extended service life of waterproofing, localized production of fresh produce, and the enhancement of courtyard "social capital." The presence of a clear co-financing model (municipal programs, grants, business partnerships) accelerates scaling, but it is critical that each solution remains viable within realistic budgets and load conditions.

Taken together, the results demonstrate that the integration of green roofs, nature-based stormwater infrastructure, and productive agro-elements into post-Soviet residential districts is technically feasible and managerially achievable, provided phased implementation, strict adherence to O&M regulations, and transparent monitoring are in place. This approach mitigates climatic and hydrological risks, enhances the quality of the urban environment, and generates sustainable added value for both residents and management organizations.

5 CONCLUSIONS

1. Integrating eco-agroarchitectural elements in the modernization of residential districts simultaneously addresses environmental, social, and food-security objectives while improving energy efficiency and overall urban environmental quality.
2. The absence of Kazakhstani precedents is not a barrier: drawing on international practice and scholarly guidance enables the launch of pilot projects that can establish new standards for design and operation.
3. Eco-agroarchitecture functions as a truly multidisciplinary modernization tool: it reduces stormwater risks and urban overheating, enhances thermal comfort and biodiversity, and stimulates a local care economy and resident cooperation. The effect is robust when solutions are integrated into a unified courtyard - block system.
4. Starter measures - extensive green roofs, rain gardens, and community gardens - deliver "quick wins" with moderate costs and low risk. They cut peak runoff, improve the microclimate, and raise social engagement; simple O&M regulations and clear roles for responsible parties are essential.
5. Rooftop greenhouses and vertical farms should be introduced as pilots on public buildings. Load calculations, integration with heat and lighting systems, and sanitary requirements are mandatory. Energy and water monitoring ($kWh/kg, L/kg$) enables rapid process adjustment and cost control.
6. System resilience rests on three pillars: reliable structural calculations and details; clear O&M protocols (seasonal inspections, cleaning, safe access); and co-governance models with resident participation, formalized through a responsibility matrix and a dedicated budget.
7. For Kazakhstan, an optimal pathway is a phased model - "quick effects - pilots - scaling up" within municipal programs and standards: typified solutions, procurement criteria, target monitoring indicators, and funding for maintenance ensure reproducibility and the wide replication of best practices.

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RESEARCH ARTICLE

ASSESSMENT OF SEISMIC RISK AND RELIABILITY BASED ON THE RESULTS OF PASSPORTIZATION

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Abstract. *In the city of Almaty, a complete certification of the housing stock of multi-apartment buildings was carried out for the first time. A total of over 10 thousand buildings were inspected. The structure of the housing stock was revealed, with groups of buildings identified based on design solutions and reliability assessment. Based on the certification results, quantitative assessments of the failure probability values for various types of buildings were obtained for the first time. Formulas for assessing the quantitative value of seismic risk were obtained. The results of seismic vulnerability assessment using the classification of buildings according to the European macroseismic scale EMS-98 and the seismic scale MSK-64(K) used in the Republic of Kazakhstan are presented. The obtained results are compared. The number of multi-story residential buildings of various design types located on tectonic faults was identified. Based on global statistical data, the number of people killed in a design earthquake was assessed. An integral assessment of the reliability (probability of failure-free operation) of the multi-story housing stock of Almaty was obtained. It was shown that the demolition of non-earthquake-resistant wooden buildings will increase the overall reliability of a group of multi-story residential buildings by almost 15%. It has been established that the most dangerous buildings are those with external load-bearing walls and an internal frame; buildings with load-bearing walls made of brickwork and precast reinforced concrete floors; buildings with a height of 2 or more floors with load-bearing walls made of brickwork and wooden floors; single-storey buildings with load-bearing walls made of brickwork. The results of the quantitative assessment of seismic risk values can be used to develop rational urban development schemes and economic assessment of the territory used.*

Keywords: *passportization, risk, building, losses, reliability, repeatability, vulnerability, tectonic faults.*

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ҒЫЛЫМИ МАҚАЛА

ПАСПОРТТАУ НӘТИЖЕЛЕРІ БОЙЫНША СЕЙСМИКАЛЫҚ ТӘУЕКЕЛ МЕН СЕНІМДІЛІКТІ БАҒАЛАУ

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Аңдатпа. *Алматы қаласында алғаш рет көппәтерлі ғимараттардың тұрғын үй қорына толық төлқұжаттау жүргізілді. Барлығы 10 мыңнан астам ғимарат зерттелді. Конструктивті шешімдер мен сенімділікті бағалау бойынша ғимараттар топтарын бөле отырып тұрғын үй қорының құрылымы анықталды. Төлқұжаттау нәтижелері бойынша алғаш рет ғимараттардың әртүрлі типтері үшін ақау пайда болу ықтималдығының сандық бағалары алынды. Сейсмикалық тәуекелдің сандық мәнін бағалауға арналған формулалар алынды. Қазақстан Республикасында қолданылатын EMS-98 еуропалық макросейсмикалық шкаласы және MSK-64(K) сейсмикалық шкаласы бойынша ғимараттардың жіктемесін пайдалана отырып, сейсмикалық осалдықты бағалау нәтижелері келтірілді. Алынған нәтижелерді салыстыру орындалды. Тектоникалық жарықтарда орналасқан әртүрлі конструктивтік типтегі көп қабатты тұрғын үйлердің саны анықталды. Статистикалық әлемдік деректер негізінде есептелген жер сілкінісі кезінде қаза тапқандар санын бағалау жүргізілді. Алматы қаласының көпқабатты тұрғын үй қорының сенімділігінің (ақаусыз жұмыс істеу ықтималдығына) интегралды бағалауы алынды. Сейсмикаға төзімді емес ағаш ғимараттарды бұзу көп қабатты тұрғын ғимараттар тобының жалпы сенімділігін 15%-ға арттыратыны көрсетілген. Ең қауіптісі сыртқы күш түсетін қабырғалары мен ішкі жақтауы бар ғимараттар; кірпіш қалаудан жасалған күш түсетін қабырғалары және құрама темірбетон жабындары бар ғимараттар; кірпіш қалаудан жасалған күш түсетін қабырғалары мен ағаш жабындары бар биіктігі 2 немесе одан да көп қабатты ғимараттар; кірпіш қалаудан жасалған күш түсетін қабырғалары бар бір қабатты ғимараттар. Ал сейсмикалық тәуекел шамаларын сандық бағалау нәтижелері ұтымды қала құрылысы, пайдаланылатын аумақты экономикалық бағалау схемаларын әзірлеу үшін пайдаланылуы мүмкін.*

Түйін сөздер: *төлқұжаттау, тәуекел, ғимарат, шығындар, сенімділік, қайталану, осалдық, тектоникалық жарықтар*.

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НАУЧНАЯ СТАТЬЯ

ОЦЕНКА СЕЙСМИЧЕСКОГО РИСКА И НАДЕЖНОСТИ ПО РЕЗУЛЬТАТАМ ПАСПОРТИЗАЦИИ

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Аннотация. *В городе Алматы впервые проведена полная паспортизация жилого фонда многоквартирных зданий. Всего было обследовано свыше 10 тысяч зданий. Выявлена структура жилого фонда с выделением групп зданий по конструктивным решениям и оценки надежности. По результатам паспортизации впервые получены количественные оценки величин вероятности отказа для различных типов зданий. Получены формулы для оценки количественного значения сейсмического риска. Приведены результаты оценки сейсмической уязвимости с использованием классификации зданий по Европейской макросейсмической шкале EMS-98 и сейсмической шкалы MSK-64(K), применяемой в Республике Казахстан. Выполнено сопоставление полученных результатов. Выявлено количество многоэтажных жилых зданий различных конструктивных типов, расположенных на тектонических разломах. На основе статистических мировых данных проведена оценка количества погибших при расчетном землетрясении. Получена интегральная оценка надежности (вероятности безотказной работы) многоэтажного жилого фонда города Алматы. Показано, что снос не сейсмостойких деревянных зданий увеличит общую надежность группы многоэтажных жилых зданий почти на 15%. Установлено, что наиболее опасными являются здания с наружными несущими стенами и внутренним каркасом; здания с несущими стенами из кирпичной кладки и сборными железобетонными перекрытиями; здания высотой в 2 и более этажей с несущими стенами из кирпичной кладки и деревянными перекрытиями; одноэтажные здания с несущими стенами из кирпичной кладки. В результаты количественной оценки величин сейсмического риска могут быть использованы для разработки схем рационального градостроительства, экономической оценки используемой территории.*

Ключевые слова: *паспортизация, риск, здание, потери, надежность, повторяемость, уязвимость, тектонические разломы.*

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CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

The authors declare that no generative artificial intelligence technologies or AI-based tools were used in the preparation of this article.

АЛҒЫС / ҚАРЖЫЛАНДЫРУ КӨЗІ

Зерттеу Қазақстан Республикасы Ғылым және жоғары білім министрлігі Ғылым комитетінің ИРН АР23485057 "Тектоникалық ақауларды паспорттау және есепке алу нәтижелері бойынша көп қабатты үйлер үшін тәуекелді статистикалық бағалау" гранттық қаржыландыру шеңберінде жүргізілді.

МҮДДЕЛЕР ҚАҚТЫҒЫСЫ

Авторлар мүдделер қақтығысы жоқ деп мәлімдейді.

Авторлар мақаланы дайындау барысында генеративті жасанды интеллект технологиялары мен жасанды интеллектке негізделген технологияларды пайдаланбағанын мәлімдейді.

БЛАГОДАРНОСТИ/ИСТОЧНИК ФИНАНСИРОВАНИЯ

Исследование проводилось в рамках грантового финансирования Комитета науки Министерства науки и высшего образования Республики Казахстан ИРН АР23485057 “Статистическая оценка риска для многоэтажных жилых домов по результатам паспортизации и учета тектонических разломов”.

КОНФЛИКТ ИНТЕРЕСОВ

Авторы заявляют, что конфликта интересов нет.

Авторы заявляют о том, что при подготовке статьи не использовались технологии генеративного искусственного интеллекта и технологии, основанные на искусственном интеллекте.

1 INTRODUCTION

The districts of the Almaty metropolis constitute the most seismically active area in Central Asia. Over the past 140 years, three strong earthquakes with magnitudes of 7 – 8 have occurred here: the Verny earthquake of 1887, the Chilik earthquake of 1889, and the Kebin (Kemin) earthquake of 1911. The current population of Almaty is about 2.0 million people, and including the suburbs, about 2.5 million. The background seismicity of the city's territory, according to the MSK-64(K) scale, is 9 points. According to the old seismic zoning map, there are extensive ten-point zones composed of soft and loose soils. The entire central part of the city is literally located on tectonic faults, some of which may be seismogenic. According to the Seismic Zoning Map of the Republic of Kazakhstan, the median peak ground acceleration is 0.38 g for a recurrence period of once in 475 years and 0.73 g for a recurrence period of once in 2,475 years (g – acceleration of gravity). Since December 12, 2019, the Republic of Kazakhstan has adopted a new construction regulatory framework based on Eurocode, which provides a probabilistic description of seismic hazard parameters and formalizes the concept of risk to a significant degree.

The first building inventory in Almaty was carried out in the late 1990s under the supervision of Academician T.Zh. Zhunusov. Recommendations for building inventory were developed, and the central part of the city was surveyed. The first seismic risk assessments for Almaty were discussed at an international expert meeting held in the city on October 22-25, 1996. It was noted that, in the event of a 9-point earthquake in the Almaty region, depending on the season and time of day, up to 75 thousand people could be killed and up to 300 thousand injured. This initiated the development of the Program for the Protection of the Population of Almaty from Earthquakes (**Lobodryga & Shardarbek, 2001; Lobodryga, 2015**).

The second building inventory – a sample survey of multi-apartment residential buildings in Almaty – was carried out in 2008 within the framework of the "Study on Seismic Risk Management in the City of Almaty, Republic of Kazakhstan" under the auspices of the Japan International Cooperation Agency (JICA). The survey showed that at least 30% of multi-apartment residential buildings were non-seismic-resistant. In works **(Lapin & Erzhanov, 2016; Lapin & Erzhanov, 2017; Aldakhov, 2019)** the problems of assessing seismic risk levels for facilities in Kazakhstan and Almaty began to be considered from the standpoint of risk theory.

2 LITERATURE REVIEW

The third certification was carried out in 2017-2018 on the basis of an agreement between the State Institution "Department of Architecture and Urban Development of Almaty" and JSC "Kazakh Research and Design Institute of Construction and Architecture" (JSC KazNIISA) **(Tuleev et al., 2018; Shokbarov, 2020)**.

The results are presented in **Table 1**. These results are, as it were, experimental data on assessing the seismic resistance of the housing stock of a specific territory.

It should be noted that during the certification, a large number of photographs were obtained for all types of buildings.

It should be noted that for the first time, when examining all buildings, the practice of shooting the objects being examined from drones was implemented. Photographic materials on shooting the objects being examined from various angles are stored for each object. **Figure 1-2** show photographs of some non-earthquake-resistant buildings.

The structure of the housing stock in any settlement, including the city of Almaty, is crucial information for assessing the levels of reliability and seismic risk for a given city or metropolis.

Based on the results of the building inventory conducted in 2017-2018 **(Lobodryga & Shardarbek, 2001)**, the complete structure of the housing stock is presented in **Table 3** (multifamily residential buildings). The risk of failure is shown in **Tables 4, 5**.

The first significant result was obtained: as a result of additional inspections of multistory residential buildings, the proportion of non-seismic-resistant buildings decreased from 33.32% to

25.90%. The explanation is fairly straightforward: modern multistory residential complexes were constructed using monolithic structural solutions.

The second significant result was that only buildings with a steel frame in Almaty can be unequivocally classified as seismic-resistant. All other building types have non-zero probabilities of failure, which applies even to relatively seismic-resistant large-panel buildings. **Figure 1** shows an example of a non-seismic-resistant large-panel building

Table 1
The structure of the housing stock of the city of Almaty - apartment buildings (2017-2018)

№	Design solution	Number of buildings	Number of non-earthquake-resistant buildings	Index of non-earthquake-resistant buildings, %	Main types of non-earthquake-resistant buildings
1	Large-panel	2658	33	1,242%	Buildings with a first flexible or brick floor
2	Brick	1607	1594	99,07%	Two-story buildings with wooden floors, four-story buildings of the 60s
3	Frame	1847	59	3,195%	Individual objects
4	Monolithic	1420	27	1,902%	Single objects
5	Wooden	627	627	100%	Two-story frame-reed with a service life of over 50 years
6	Metal-frame	12	–	–	–
	Total	8171	2340	33,32%	

Figure 1 – Large-panel building with a flexible first floor, Mynbayev str.47 (author’s material)

Figure 2 – Brick building, Shcherbakov str.16 (author’s material)

Table 2
Results of the passportization of residential multi-storey residential buildings (MSRB) in 2024

Series of multi-storey residential buildings	Quantity	Non-earthquake-resistant buildings
IPkar	300	195
IPmon	1402	-
158	2	-
1Кз-464-AS	1	-
1Кз-464DS	4	-
308	2	-
69	1	-
VP	3	-
VT	2	-
IP kir	36	36
IPder	7	7
IPmetal	6	-
Reed panel frame buildings	5	5
СЖКУ (SZHKU)	2	-
СЖКУ-9 (SZHKU-9)	1	-
No buildings	3	3
total:	1777	246

Table 3
Complete structure of the housing stock of the city of Almaty according to all passports - apartment buildings

№	Design solution	Number of buildings	Number of non-earthquake-resistant buildings	Index of non-earthquake-resistant buildings, %	Probabilities of failure risk
1	Large-panel	2666	33	1,238%	Buildings with a first flexible or brick floor, built in an economic way.
2	Brick	1645	1624	98,723%	Two-story buildings with wooden floors, four-story buildings of the 60s
3	Frame	2155	251	11,647%	Individual objects
4	Monolithic	2822	27	0,957%	Single objects
5	Wooden	639	639	100%	Two-story frame-reed with a service life of over 50 years
6	Metal-frame	18	–	–	–
7	Unfinished	3	3		
	Total	9948	2577	25,90%	

Table 4
Failure risk probabilities for different building types

№	Design solution	Number of buildings	Number of non-earthquake-resistant buildings	Index of non-earthquake-resistant buildings, %	Probabilities of failure risk
1	Large-panel	2666	33	1,238%	0.0124
2	Brick	1645	1624	98,723%	0.9872
3	Frame	2155	251	11,647%	0.1165
4	Monolithic	2822	27	0,957%	0.0096
5	Wooden	639	639	100%	1
6	Metal-frame	18	-	-	0
7	Unfinished	3	3		1
	Total	9948	2577	25,90%	

Table 5
Failure risk probabilities for different building types

№	Design solution	Probability of a building of this type	Probabilities of failure risk	Probabilities of risk of failure of buildings of this group
1	Large-panel	0.2680	0.0124	0.0033
2	Brick	0.1654	0.9872	0.1633
3	Frame	0.2166	0.1165	0.0252
4	Monolithic	0.2837	0.0096	0.0027
5	Wooden	0/0642	1	0/00642
6	Metal-frame	0/0018	0	0.0
7	Unfinished	0.00030	1	0.0030

3 MATERIALS AND METHODS

Below are the average values of economic damage U of buildings by groups of buildings according to the data of Khakimov Sh.A. **Figure 3**, which were obtained during the analysis of the consequences of strong earthquakes in Central and Middle Asia **(Khakimov & Nurtaev, 2003; Khakimov & Nurtaev, 2005; Khakimov, 2001)**. Note that here there is a connection between the earthquake score and the average damage in % of the initial cost.

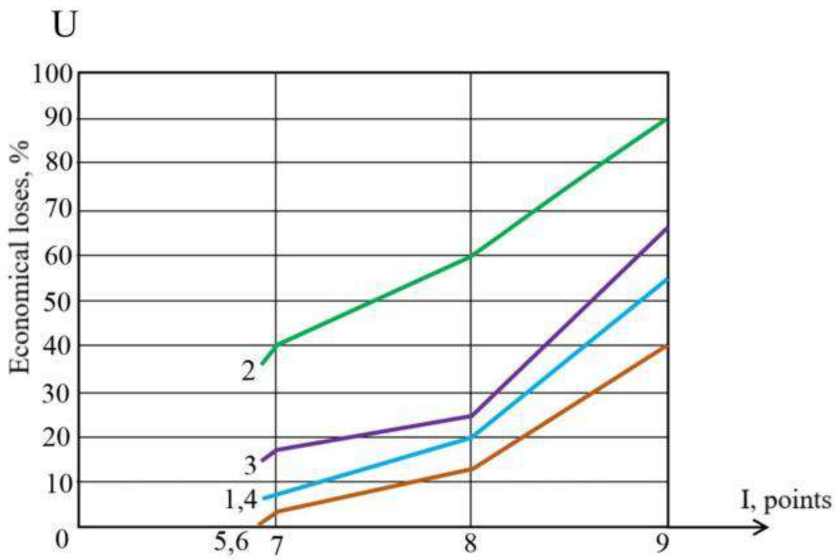

Figure 3 – Regression dependences of damage on the intensity of impact in points on a scale MSK-64 (K). (author's material)

Using the data in **Table 2** and the previous calculations, we can estimate the seismic risk R.

Using the classical definition of risk as the product of the probability of failure Q and the value of the loss function **(Seismic Risk and Engineering Solutions, 1981)**.

$$R = QU, \quad (1)$$

where U is the damage from failure as a share of the initial cost of the object. Then, according to the data in **Table 2**, for the risk value we write

$$R=0.55 \cdot N_1 Q_1 U_1 + N_2 \cdot Q_2 U_2 + N_3 \cdot Q_3 U_3 + 0.55 \cdot N_4 Q_4 + 0.40 \cdot N_5 Q_5 U_5 + 0.40 \cdot N_6 Q_6 U_6, \quad (2)$$

where Ui – average damage to a building from *the i-th* group of buildings, *Ni* is the number of non-earthquake-resistant buildings in each group from **Table 2**. The values of *Qi* can be taken from **Table 2** for a particular value of repeatability.

Taking into account N_6=0, we will have a regression dependence

$$R=0.55 \cdot N_1Q_1U_1+N_2 \cdot Q_2U_2+N_3 \cdot Q_3U_3+0.55 \cdot N_4Q_4+0.40 \cdot N_5Q_5U_5 \quad (3)$$

By substituting the values of the average initial cost, it is possible to obtain a quantitative risk assessment.

Formula 3 is fairly simple and straightforward. If all old wooden buildings had been demolished in time, then N_5=0, and the damage value would decrease significantly. The same reasoning can be applied to any building group. The damage shares relative to the initial cost are taken from the works of Khakimov Sh.A.

It is clear that classical approaches to assessing building reliability as the probability of not reaching a specified damage level are also feasible for implementation **(Khakimov, 2001; Raizer, 2010; Seismic Risk and Engineering Solutions, 1981; Dzhinchvelashvili et al., 2018; Aizenberg, 1978; Aizenberg, 2004; Raizer, 2007; Tsipenyuk, 1987; Napetvaridze, 1985; Lapin, 1998)** and it is planned to use them in further research.

Let us discuss the presence of a correlation between seismic impact intensity and the degree of building damage. **Table 5** presents the degrees of damage for each building type at a given seismic intensity. The correlation coefficient was calculated using the MATLAB software package.

Table 6

Correlation coefficients between earthquake magnitude and damage extent

№	Design solution	7 points	8 points	9 points	Correlation coefficients
1	Large panel	7	20	55	0.9667
2	Brick	40	60	90	0.9934
3	Frame	18	25	65	0.9267
4	Monolithic	7	20	55	0.9667
5	Wooden	3	12	40	0.9588
6	Metal-frame	3	12	40	0.9588
7	Unfinished				

The correlation coefficient is quite high. Therefore, the assessment of the degree of damageability and loss appears to be reliable.

Example 1. Let us estimate the overall reliability W_0 of multi-storey residential buildings in the city of Almaty. According to **Table 5**, the probability of failure for the city's facilities is Q=0.2617. Therefore, the overall reliability is W_0 = 1-Q= 0.7383.

Example 2. How will the value of the total probability of failure-free operation of WO change under the condition of complete demolition of all wooden buildings **Table 5** (639 units).

The probability of failure for the group of wooden buildings will become equal to 1, and according to **Table 4**, Q=0,1975. Therefore, the overall reliability will be:

$$W_0=0{,}8025.$$

The change in overall reliability will amount to 8%, which is quite significant. The demolition of wooden buildings should therefore be carried out.

The expression for the risk values will then take the form

$$R=0.55 \cdot N_1Q_1U_1+N_2 \cdot Q_2U_2+N_3 \cdot Q_3U_3+0.55 \cdot N_4Q_4 \quad (4)$$

Example 3. How will the values of the total probability of failure-free operation W_0 change under the condition of total reinforcement of large-panel buildings in **Table 1** (33 units).

The probability of failure for the group of large-panel buildings will become equal to 0. Then, according to the results of **Table 5**, Q = 0,2584 and Q_0 = 0.26413:

$$W_0=0.7416$$

The change in overall reliability is about 1.0%, which is not significant. An obvious conclusion follows: reinforcing large-panel buildings in the city of Almaty should be the last priority.

Finally, we will obtain estimates for human losses in the event of a possible design-level earthquake. Such estimates were first obtained during the second certification of the city of Almaty.

4 RESULTS AND DISCUSSION

There are various methods for predicting losses. It appears that all these methods are rather imperfect, with deviations reaching several hundred percent. Therefore, the statistical assessment confirmed during the 1988 Spitak earthquake **(Khachiyan, 2018)** seems well justified. According to global statistical data, the number of fatalities in earthquakes for developing countries can be estimated as follows.

In cities of developing countries:

For an 8-point earthquake on the MSK and ESC scales, on average, 0.5% of the population dies, and 2% are injured.

For a severe 9-point earthquake, on average, 5% of the population dies, and 20% sustain serious injuries.

Assuming that the total population of Almaty, including temporary residents, is 2.5 million people, the number of fatalities in an 8-point earthquake would average 12,500 people, with 50,000 injured.

In a 9-point earthquake, the fatalities would amount to 125,000, with up to 500,000 injured.

It should be emphasized that these are average estimates. The latter estimate correlates well with expert assessments from 1996, when the city's population was around 1.1 million.

This is a realistic assessment. After all, Almaty has a fairly extensive history of earthquake-resistant construction – about 60 years. The seismic construction standards are quite strict.

As a result of the passportization, the buildings were examined in terms of a macroseismic assessment according to the EMS-98 scale **(Rashid et al., 2023)**. Residential buildings were classified by type and plasticity class. They were then assigned to six vulnerability classes according to EMS-98. The degree of structural damage is assessed from slight damage to complete collapse, within a range of five levels. The expected mean damage was correlated with various seismic intensities and peak ground acceleration (PGA) values. The probability of damage was assessed for recurrence intervals of once in 475 years and once in 2,475 years.

The results of the EMS-98 assessment correspond to the conclusions of this article obtained using the MSK-64 seismic intensity scale. For masonry-walled and wooden buildings, the mean damage is very high for both earthquake recurrence intervals. The expected mean damage for reinforced concrete and precast reinforced concrete buildings with medium plasticity is rather moderate.

Buildings with steel frames will have an insignificant level of damage. This is a rare case where two methods of seismic risk assessment were applied using empirical passportization data.

5 CONCLUSIONS

1. At present, as a result of the building certification process for the city of Almaty, objective information has been obtained on the seismic resistance of six groups of multi-apartment residential buildings. This data makes it possible to carry out a quantitative assessment of seismic risk values.

2. The most hazardous are buildings with external load-bearing walls and an internal frame; buildings with load-bearing walls of brick masonry and precast reinforced concrete floors; buildings

two or more stories high with load-bearing brick masonry walls and wooden floors; one-story buildings with load-bearing brick masonry walls and wooden beam floors with normal masonry bond strength of less than 120 kPa (1.2 kg/cm²); as well as wooden buildings constructed in the 1950s without seismic-resistant measures.

3. Within the framework of the phenomenological approach, values of failure probability have been obtained for the six groups of buildings. Formulas have been derived from the quantitative assessment of seismic risk values.

4. The results of the certification indicate insufficient seismic resistance of buildings with load-bearing brick walls, 99% of which were found to be non-seismic-resistant. The seismic resistance of such buildings can be ensured only by using various types of seismic isolation systems or by the widespread application of energy-absorbing elements. JSC KazNIISA has extensive experience in applying various types of seismic isolation systems. Only the use of such systems will make it possible to prevent mass casualties and the loss of material assets. It should be remembered that in 1911 the Kemin earthquake had a magnitude of 8.2, was of a seismic disaster nature, and was felt over an area of 2 million square kilometers.

5. The results of the quantitative assessment of seismic risk values can be used for the development of schemes for the rational use of land resources, rational urban planning, economic evaluation of the utilized territory, and for providing information support for various works related to assessing the seismic hazard of the environment.

6. Research should be continued in the areas of the influence on building reliability of the following factors: quality of surveys, design, materials, and construction; technical condition, physical deterioration, specific features of operation, presence of vibration loads, and level of engineering protection.

7. Based on the results of the 2017-2018 certification, adjustments should be made to the certification card, taking into account both the experience gained and the experience of other EAEU countries. Particular attention should be paid to modern foreign studies on determining seismic risk values.

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RESEARCH ARTICLE

STRENGTHENING OF STRENGTH OF REINFORCED CONCRETE RAILWAY SLEEPERS UNDER DYNAMIC EFFECTS

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Abstract. *In order to increase the resistance of sleepers to dynamic effects and to strengthen their load-bearing capacity, it is important to investigate their internal strength reserve to various external effects, including the ductility of the subgrade. This is due to the insufficient theoretical and experimental studies to predict their strength reserve in modern conditions. The aim of this research is to improve the dynamic calculation of railway sleepers by developing more accurate calculation models and using modern algorithms to determine their bearing capacity. To achieve this goal, the paper uses analytical and numerical methods based on mathematical models. The base of sleepers is continuous elastic. Methods for determining the natural frequencies of transverse vibrations and a dynamic calculation method for determining the stress-strain state at different load speeds and base stiffness are presented. An example of calculation of railway sleepers is presented. The values of natural frequencies for different forms of vibrations are determined by analytical and numerical methods, and the results are compared. Static and dynamic calculations were carried out, as a result of which the values of internal forces, values of deflections and normal stresses were obtained. Evaluation of the obtained results is given. Strength reserve has been determined and appropriate conclusions have been drawn.*

Keywords: *railway sleepers, elastic base, natural frequencies, stresses, deformations.*

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ҒЫЛЫМИ МАҚАЛА

ДИНАМИКАЛЫҚ ӘСЕРІНЕН ТЕМІР ЖОЛДАРДЫҢ ТЕМІРБЕТОН ШПАЛДАРЫНЫҢ БЕРІКТІГІ КҮШЕЙТУ

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Аңдатпа. *Шпалдардың динамикалық әсерге төзімділігін арттыру және олардың көтергіштігін арттыру үшін олардың беріктігінің ішкі резервін әртүрлі сыртқы әсерлерге, соның ішінде негіздің беріктігіне зерттеу маңызды. Бұл қазіргі жағдайда олардың беріктік резервін болжау үшін жеткілікті теориялық және эксперименттік зерттеулерден туындамайды. Бұл зерттеулердің мақсаты дәлірек есептеу модельдерін жасау және олардың жүк көтергіштігін анықтау үшін заманауи алгоритмдерді қолдану арқылы теміржол байланыстарының динамикалық есебін жетілдіру болып табылады. Осы мақсатқа жету үшін жұмыста математикалық модельдерге негізделген аналитикалық және сандық әдістер қолданылады. Шпалдардың негізі қатты серпімді. Көлденең ауытқулардың нақты жиіліктерін анықтау және жүктеме мен негіздің қаттылығының әртүрлі жылдамдықтарындағы кернеулі деформацияланған күйді анықтау үшін динамикалық есептеу әдістері ұсынылған. Теміржол байланыстарын есептеу мысалы келтірілген. Аналитикалық және сандық әдістердің көмегімен ауытқудың әртүрлі формалары үшін нақты жиіліктердің мәндері анықталды, сонымен қатар нәтижелерді салыстыру жүргізілді. Статикалық және динамикалық есептеулер жүргізілді, нәтижесінде ішкі күштердің мәндері, иілу мәндері және қалыпты кернеулер алынды. Алынған нәтижелер бағаланды. Беріктік резерві анықталды, тиісті қорытындылар жасалды.*

Түйін сөздер: *теміржол шпалдары, серпінді негізі, меншікті жиілігі, кернеу, деформация*

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НАУЧНАЯ СТАТЬЯ

УСИЛЕНИЕ ПРОЧНОСТИ ЖЕЛЕЗОБЕТОННЫХ ШПАЛ ЖЕЛЕЗНЫХ ДОРОГ ПРИ ДИНАМИЧЕСКИХ ВОЗДЕЙСТВИЯХ

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Аннотация. *Для повышения сопротивления шпал динамическим воздействием и усиления их несущей способности важным является изучение внутреннего резерва их прочности на различные внешние воздействия, включая прочность основания. Это вызвано недостаточно теоретическими и экспериментальными исследованиями для прогнозирования их резерва прочности в современных условиях. Целью данных исследований является совершенствование динамического учета железнодорожных шпал путем использования современных алгоритмов для разработки более точных вычислительных моделей и определения их несущей способности. Для достижения этой цели в работе используются аналитические и количественные методы, которые основаны на математических моделях. Основание шпал является сплошным упругим. Предложены методы определения удельных частот поперечных отклонений и динамического расчета по определению напряженно-деформированного состояния при различных скоростях движения нагрузки и жесткости основания. Представлен пример расчета железнодорожных шпал. С помощью аналитических и количественных методов определены значения удельных частот для различных форм отклонений, а также было проведено сравнение результатов. Были проведены статические и динамические расчеты, в результате которых были получены значения внутренних сил, значения изгибов и нормальных напряжений. Полученные результаты были оценены. Определен резерв прочности, сделаны соответствующие выводы.*

Ключевые слова: *железнодорожные шпалы, упругое основание, частота колебаний, напряжение, деформация.*

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CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

During the preparation of this manuscript, the authors used artificial intelligence tools (ChatGPT) solely for editorial assistance, such as improving phrasing and checking grammar, spelling, and punctuation. All ideas, interpretations, and conclusions are the responsibility of the authors, who take full accountability for the content of the article.

АЛҒЫС / ҚАРЖЫЛАНДЫРУ КӨЗІ

Зерттеу жеке қаржыландыру көздерін пайдалана отырып жүргізілді.

МҮДДЕЛЕР ҚАҚТЫҒЫСЫ

Авторлар мүдделер қақтығысы жоқ деп мәлімдейді.

Мақаланы дайындау барысында авторлар жасанды интеллект құралдарын (ChatGPT) тек редакциялық көмек мақсатында пайдаланды: тұжырымдарды жетілдіру, грамматикалық, орфографиялық және тыныс белгілеріндегі қателерді тексеру үшін. Барлық идеялар, интерпретациялар мен қорытындылар авторларға тиесілі, және олар мақаланың мазмұнына толық жауапты.

БЛАГОДАРНОСТИ/ИСТОЧНИК ФИНАНСИРОВАНИЯ

Исследование проводилось с использованием частных источников финансирования.

КОНФЛИКТ ИНТЕРЕСОВ

Авторы заявляют, что конфликта интересов нет.

При подготовке рукописи авторы использовали инструменты искусственного интеллекта (ChatGPT) исключительно для редакторской поддержки: корректировки формулировок, проверки грамматических, орфографических и пунктуационных ошибок. Все идеи, интерпретации и выводы принадлежат авторам, которые несут полную ответственность за содержание статьи.

1 INTRODUCTION

An important aspect of the development of railway tracks and their improvement is traffic safety, which depends on the quality of the track, its strength, stability and durability. One of the important elements of the reliability of the railway track are reinforced concrete sleepers, which ensure the stability of the rails, reducing the likelihood of subsidence when moving trains.

A railway track is a complex open technical system that interacts with its environment - other transport and non-transport technical systems and the natural environment.The design of a railway track must have coordinated physical and mechanical parameters of its constituent elements and, when a train is moving, accumulate a minimum of potential energy and dissipate this energy in a uniform flow through deformation of materials and relative displacements of the design elements. Sleepers play a key role in ensuring the operational characteristics of the track and safety in rail transport. They are designed to distribute the load from passing trains on the ballast, as well as to hold the rail strings in place, preventing their shift or movement. A reinforced concrete sleeper is a solid bar structure made of reinforced concrete with high-strength reinforcement, which must meet all the requirements of the standard **(Figure 1)**.

In the conditions of increasing the carrying capacity and intensity of freight turnover on the railways of the Republic of Kazakhstan, it is necessary to increase the requirements for traffic safety, one of the areas for this is the study of the strength and reliability of reinforced concrete sleepers capable of withstanding dynamic impacts.

Let us note some theoretical and experimental studies of the strength and reliability of railway sleepers, which reflect monitoring and innovative developments according to research by **(Mirsayapov, 2022)**. For example, methods for calculating the endurance and crack resistance of reinforced concrete sleepers with prestressed rod reinforcement under cyclic loads.

The studies by **(Gnezdilov et al., 2023)** demonstrate that an innovative diagnostic complex is used to determine and evaluate the stress–strain state of reinforced concrete sleepers on sections of heavy-duty trains under dynamic loads. A review of materials for reinforced concrete sleepers is given, and the main types of failure of prestressed concrete sleepers under cyclic and impact loads are indicated.

The studies by **(Mirzakhidova, 2021)** present the design features of reinforced concrete sleepers depending on the types of rail fastening to the sleeper, the type of tensioned reinforcement, the presence of electrical insulating properties, and the overall quality of manufacture. The COSMOS/M software system was used for the calculations.

Despite the fact that theoretical and diagnostic studies of the stress-strain state of reinforced concrete sleepers are constantly being conducted, the available data are insufficient to predict their strength reserve under modern conditions. For example, one of the disadvantages of reinforced concrete sleepers is their sensitivity to impacts (especially at the joints), and their insufficient rigidity contributes to rapid wear of the rails at the joints. At the same time, the increased rigidity of reinforced concrete sleepers can contribute to an increase in the dynamic impact of rolling stock on the ballast and on the roadbed, which leads to a more intensive accumulation of track settlements and an increase in the volume of alignment work, especially at the joints. The peculiarity of the sleepers' operation under dynamic influences and their neglect shows numerous defects in the sleepers, which leads to increased labor costs. For effective operation of sleepers, it is necessary to develop clear criteria for their use, a systematic approach to research and the use of accurate mathematical methods.

To increase the resistance of sleepers to dynamic impact and to enhance their bearing capacity, it is necessary to study their internal reserve of strength to various external impacts, including the flexibility of the base as considered in the work of **(Leontiev, 2020)**.

2 LITERATURE REVIEW

The purpose of these studies is to improve the dynamic calculation of railroad sleepers by developing more accurate calculation models and using modern algorithms to enhance their bearing capacity.

To achieve this goal, analytical and numerical methods are used, based on mathematical models of sleepers, verified by experimental data.

In engineering practice, beam elements of structures lying on a continuous elastic foundation are often encountered. Such structures may include railroad sleepers, strip foundations of buildings, dam foundations resting on soil, various types of pipelines laid on or inside the soil, etc.

In the following, a beam with an uneven cross-section lying on an elastic foundation is adopted as the design scheme for railway sleepers. Concentrated dynamic loads varying according to a harmonic law with frequency θ are considered as external influences, as described by **(Mirsayapov, 2022) (Figure 1)**.

Figure 1 – Railway sleepers **(Mirsayapov, 2022)**

When calculating sleepers, it is assumed that the soil has elastic properties and its deformation is proportional to the applied load. In addition to this basic premise, other assumptions are also made when calculating beams on an elastic foundation:

- there is no friction between the base and the beam;
- the elastic base is uniform along the entire length of the beam and the width of the beam bed is constant;

One of the most common hypotheses is the hypothesis of a proportional relationship between reaction and settlement—the Winkler foundation hypothesis. The calculation scheme of a beam on an elastic foundation is shown in **Figure 2**, as presented by **(Gnezdilov et al., 2023)**:

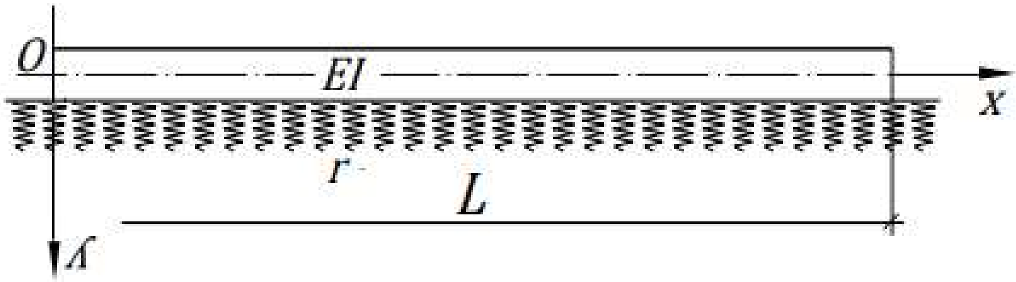

Figure 2 – Calculation scheme of a beam on an elastic foundation (Gnezdilov S.A., 2023).

3 MATERIALS AND METHODS

The research methods consist of 2 parts: the first part is devoted to determining the dynamic characteristics of the system under consideration, and the second part is devoted to the dynamic calculation of railway sleepers, as a result of which their bearing capacity and deformability at high train speeds are clarified.

3.1 Definition of dynamic characteristics

Let us consider the natural oscillations of a beam with a constant mass lying on an elastic foundation. Assuming the external load to be zero, the equation of natural oscillations takes the form as presented by **(Dostanova et al., 2024)**:

$$EI\frac{\partial^4 y(x,t)}{\partial x^4} + m\frac{\partial^2 y(x,t)}{\partial t^2} + rby(x,t) = 0 \tag{1}$$

In (1) y(x,t) is the deflection function, EI is the bending rigidity, m is the linear mass, r is the elastic foundation rigidity. b is the beam width.

Considering periodic oscillations of a beam with a frequency ω, then the deflections can be represented as the following sum of natural oscillations:

$$y(x,t) = \sum_{k=1}^{\infty} y_k\ (x)\, T_k(t) \quad \text{or}$$

$$y(x,t) = \sum_{k=1}^{\infty} y_k\ (x)\, Sin\omega_k t \tag{2}$$

Substituting (2) into (1), reducing by $\sin\omega t$ for the “k” mode of vibrations, we obtain the following equation

$$EI\frac{\partial^4 y_k(x)}{\partial x^4} - \left[\frac{m\omega_k^2 - rb}{EI}\right] y_k(x) = 0 \tag{3}$$

In the following we will denote the frequency parameter

$$\lambda_k = \sqrt[4]{\left[\frac{m\omega_k^2 - rb}{EI}\right]}$$

The boundary conditions are as follows:

$$x=0 \quad M(0)=Q(0)=0 \tag{3}$$
$$x=L \quad M(L)=Q(L)=0 \tag{4}$$

We use the initial parameter method to solve equation (3), assuming two initial parameters $M_0=Q_0=0$, then the solution to the homogeneous equation can be written as:

$$\begin{gathered} y_k^0(x) = y_0 S(\lambda_k x) + \frac{\varphi_0}{\lambda_k} T(\lambda_k x) \\ \varphi_k^0(x) = y_0 \lambda_k V(\lambda_k x) + \varphi_0 S(\lambda_k x) \\ M_k^0(x) = -EIy_0\lambda_k^2 U(\lambda_k x) - EI\varphi_0 \lambda_k V(\lambda_k x) \\ Q_k^0(x) = -EIy_0\lambda_k^3 T(\lambda_k x) - EI\varphi_0 \lambda_k^2 U(\lambda_k x) \end{gathered} \tag{5}$$

k=1,2,3………

In (5) the following circular functions are introduced

$$S(\lambda_k x) = \frac{1}{2}(ch\lambda_k x + cos\lambda_k x)$$
$$U(\lambda_k x) = \frac{1}{2}(ch\lambda_k x - cos\lambda_k x)$$
$$T(\lambda_k x) = \frac{1}{2}(sh\lambda_k x + sin\lambda_k x)$$

$$V(\lambda_k x) = \frac{1}{2}(sh\lambda_k x - sin\lambda_k x) \quad (6)$$

Unknown initial parameters deflection y_0 and rotation angle φ_0 are determined from the boundary conditions (3,4):

$$M_k^0(\lambda_k L) = -EIy_0\lambda_k^2\, U(\lambda_k L) - EI\varphi_0\lambda_k V(\lambda_k L) = 0$$
$$Q_k^0(\lambda_k L) = -EIy_0\lambda_k^3 T(\lambda_k L) - EI\varphi_0\lambda_k^2 U(\lambda_k L)=0 \quad (7)$$

Equations (7) represent a system of two homogeneous algebraic equations with respect to two unknown initial parameters (y_0, φ_0), since the solution must be different from zero, we assume that the determinant of the system is zero:

$$D = U^2(\lambda_k L) - V(\lambda_k L) \cdot T(\lambda_k L) = 0 \quad (8)$$

Equation (8) is a transcendental equation with respect to the parameter λk. The solution can be obtained by an approximate method.

To solve (8), we use an iterative process for the parameter λ in the range of ω [π/2 - 2π]. We introduce the function

$$F(\lambda_k) = U^2(\lambda_k L) - V(\lambda_k L) \cdot T(\lambda_k L) = 0 \quad (9)$$

Let us designate

$$A = U^2(\lambda_k L) \quad and \quad B = V(\lambda_k L) \cdot T(\lambda_k L)$$

Then equation (8) can be replaced by the equation:

A-B=0 or A=B

By specifying different values of λ_k, the values of A and B are determined. This process can be linearized. The iterative process continues until the value of the function reaches the required accuracy $F(\lambda_k)=A-B<\varepsilon$, where ε is a sufficiently small number characterizing the required accuracy of the calculation.

Having determined λ_k, the natural frequency of oscillations is determined by the formula:

$$\omega_k = \sqrt[4]{\left[\frac{EI\lambda_k^4 + rb}{m}\right]} \quad (10)$$

k=1,2,3…………

3.2 Dynamic calculation

Let us consider the forced vibrations of a beam with a constant mass. The equation of forced vibrations takes the form as presented by **(Pichkurova, 2025)**,

$$EI\frac{\partial^4 y(x,t)}{\partial x^4} + m\frac{\partial^2 y(x,t)}{\partial t^2} + rby(x,t) = q(x,t) \quad (11)$$

If the external load changes according to the harmonic law with frequency θ, i.e. $y(x,t)=sin\theta t$, then it can be assumed that the beam also oscillates according to the harmonic law with the same frequency θ. The solution of equation (11) can be expanded as a series and presented as the following sum:

$$y(x,t) = \sum_{k=1}^{\infty} y_k(x) sin\theta_k t \quad (12)$$

Substituting (12) into (11), reducing by $\sin\theta t$ for the "k" mode of oscillations, we obtain the following equation

$$EI\frac{\partial^4 y(x)}{\partial x^4} - \left[\frac{m\theta_k^2 - rb}{EI}\right] y_k(x) = q_0(x) \tag{13}$$

In (13) q_0 is the amplitude value of the external load. In the following, by analogy with natural oscillations, we denote

$$\lambda_k = \sqrt[4]{\left[\frac{m\theta_k^2 - rb}{EI}\right]} \tag{14}$$

Equation (13) is an ordinary differential equation. Solution (13) can be represented as the sum of the solution of the homogeneous equation and a particular solution:

$$y_k(x) = y_k^o(x) + y_k^{част}(x) \tag{15}$$

When considering forced vibrations of beamswith a uniformly distributed mass m, we consider the case when a concentrated external moving load F changes according to a harmonic law with a frequency θ (for the case of an arbitrary load, we use the expansion according to the norms of natural vibrations):

$$F = F_0 sin(\frac{\pi t}{T_0}), \tag{16}$$

where F_0 is the wheel load distributed over the area of a circle of diameter D, $T_0 = \frac{D}{V}$, V is the speed of horizontal movement of the load, t is the current time. Denoting the ratio π/T_0 through θ, then the external load can be represented as $F = F_0 sin(\theta \cdot t)$, where θ is the frequency of oscillations of the external load.

In the case of the action of two concentrated forces F (Figure 3), the solutions for the two sections are given as presented by **(Dostanova et al., 2024)**:

At $0 \leq x \leq a$

$$\begin{gathered} y_k(x) = y_0 S(\lambda_k x) + \frac{\varphi_0}{\lambda_k} T(\lambda_k x) \\ \varphi_k(x) = y_0 \lambda_k V(\lambda_k x) + \varphi_0 S(\lambda_k x) \\ M_k(x) = -EI y_0 \lambda_k^2 U(\lambda_k x) - EI\varphi_0 \lambda_k V(\lambda_k x) \\ Q_k(x) = -EI y_0 \lambda_k^3 T(\lambda_k x) - EI\varphi_0 \lambda_k^2 U(\lambda_k x) \\ k=1,2,3\ldots\ldots\ldots \end{gathered} \tag{17}$$

At $a \leq x \leq L$

$$\begin{gathered} y_k(x) = y_0 S(\lambda_k x) + \frac{\varphi_0}{\lambda_k} T(\lambda_k x) + \frac{FV(\lambda(x-a))}{\lambda^3 EI} \\ \varphi_k(x) = y_0 \lambda_k V(\lambda_k x) + \varphi_0 S(\lambda_k x) + \frac{FU(\lambda(x-a))}{\lambda^2 EI} \\ M_k(x) = -EI y_0 \lambda_k^2 U(\lambda_k x) - EI\varphi_0 \lambda_k V(\lambda_k x) - \frac{FT(\lambda(x-a))}{\lambda} \\ Q_k(x) = -EI y_0 \lambda_k^3 T(\lambda_k x) - EI\varphi_0 \lambda_k^2 U(\lambda_k x) - FS(\lambda(x-a)) \end{gathered} \tag{18}$$

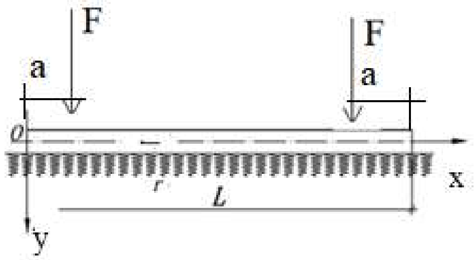

Figure 3 – The action of concentrated external forces **(Dostanova et al., 2025)**

In (17) and (18) the parameter$\lambda_k$is expressed as:

$$\lambda_k = \sqrt[4]{\left[\frac{m\theta_k^2 - rb}{EI}\right]}$$

Initial parameters y_0 and φ_0 under forced oscillations are determined from the boundary conditions:

x=L M(L)=Q(L)=0

$$-EIy_0\lambda_k^2\, U(\lambda_k L) - EI\varphi_0\lambda_k V(\lambda_k L) = \frac{FT(\lambda(L-a))}{\lambda} \quad (19)$$

$$-EIy_0\lambda_k^3 T(\lambda_k L) - EI\varphi_0\lambda_k^2 U(\lambda_k L) = FS(\lambda(L-a))$$

Due to symmetry, equations (19) have the form:

At $a \leq x \leq L$

x=L/2 φ(L/2)=0, Q(L/2)=0

$$\varphi_k(L/2) = y_0\lambda_k V(\lambda_k L/2) + \varphi_0 S(\lambda_k L/2) + \frac{FU(\lambda(L/2-a))}{\lambda^2 EI} = 0$$

$$Q_k(L/2) = -EIy_0\lambda_k^3 T(\lambda_k L/2) - EI\varphi_0\lambda_k^2 U\left(\frac{\lambda_k L}{2}\right) - FS\left(\lambda\left(\frac{L}{2} - a\right)\right) = 0 \quad (20)$$

Having determined the initial parameters from (20), the deflections, rotation angles, bending moment and shear force are determined from expressions (17,18).

4 RESULTS AND DISCUUION

The most common reinforced concrete sleepers on the railway in the Republic of Kazakhstan—type Sh1-1, used for high-speed lines—were selected for research, as presented by **(Dostanova et al., 2024)**:.

Characteristics of reinforced concrete sleepers type Ш1-1: track width - 1520 mm, dimensions: length - 2700 mm; height - 150 mm; width - 300 mm, material - prestressed reinforced concrete **(Figure 4)**.

Concrete compressive strength class – B40 (M500). E=36x10^3MPa, specific gravity of concrete γ=2.5 t/m^3. Distance between stop edges of different ends of sleeper – L=2016 mm, stop edge angle – 55^0, sleeper sub-section height – 193 mm, sleeper average section height – h=145 mm, fastening type KB-65.

The train speeds are considered in the range from 60 to 140 km/h (Figure 4), as presented by **(Dostanova et al., 2025)**:.

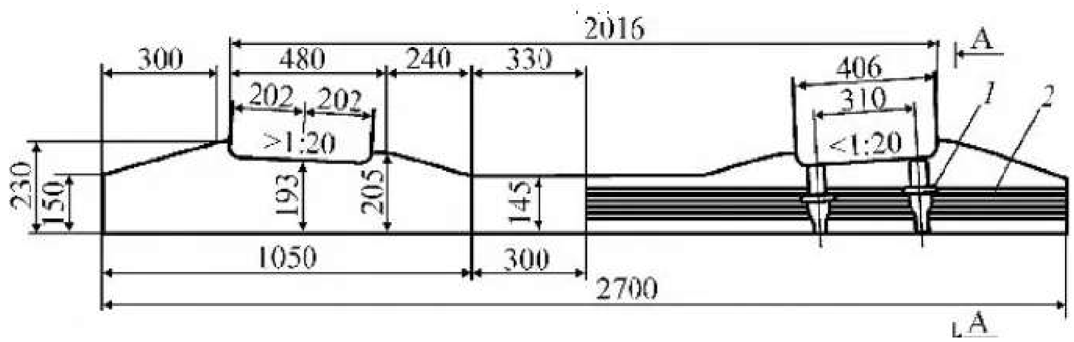

Figure 4 – Reinforced concrete sleeper type Sh1-1 **(Dostanova et. al., 2025)**

Rigidity of the base or values of the sleeper bedding coefficient, MN/m^3:

for soil base without ballast: 8... 12

for sand ballasts: 15...40

for gravel ballasts: 40...60

for crushed stone ballast: 60... 100

In the following, we consider crushed stone ballast with a sleeper bedding coefficient in the range from 60 to 80 MN/m^3. In the following, we present the results for r=60 MN/m^3.

Figure 5 shows the numbers of the sections and points at which deflections, bending moments, shear forces, and the corresponding stresses are determined, as presented by **(Dostanova et al., 2025)**:.

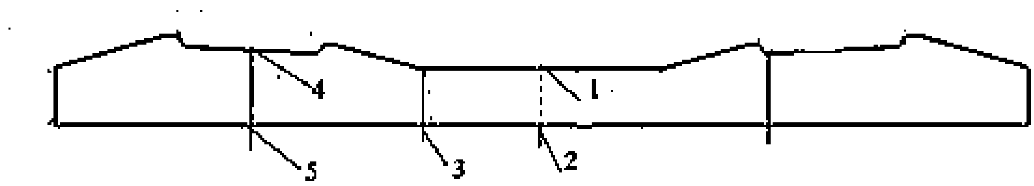

Figure 5 – Nnumbers of sections and points at which forces and deformations are determine **(Dostanova et. al., 2025)**

The moment of inertia of section 4-5 is: I=30417.5 cm^4; section 1-2: I=7621.5 cm^4, in section 3: I=8437.5 cm^4, respectively, the moments of resistance of the sections are: section 4-5 is: W=2645.5 cm^3; section 1-2: W=1051.2 cm^3 in section 3: W=1125.0 cm^3. The calculation is carried out in the elastic stage of the system operation and consists of 2 parts: determination of the dynamic characteristics and determination of the stress-strain state of reinforced concrete sleepers when the train is moving at a given speed.

The natural frequencies of oscillations are determined analytically and numerically using the COSMOS/M software system. In the latter, the STAR module presents the calculation of the stress-strain state and the calculation of the displacements of a reinforced concrete sleeper.

Figure 6 shows the shape of the natural oscillations corresponding to the first harmonic, obtained as a result of numerical calculations, as presented by **(Dostanova et. al., 2025)**.

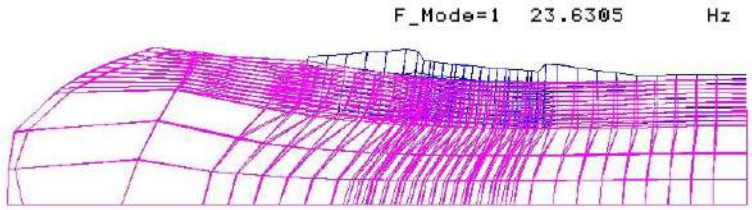

Figure 6 – The shape of natural oscillations corresponding to the 1st harmonic **(Dostanova et. al., 2025)**

Table 1 shows the natural frequencies of oscillations of the Ш1 sleeper, ω Hz, corresponding to the first harmonics.

Table 1
Natural frequencies of oscillations

Form No.	Analytical calculation	Numerical calculation	Errors in %
1	22,51	23.63	4,7
2	30,77	31.8	3,2
3	38,72	40.48	4,3
4	41,47	42.77	3,0
5	47,35	46.97	0,8

From **Table 1** it is evident that the natural frequencies determined analytically have lower values in comparison with the numerical method; with an increase in the vibration modes, their values almost coincide.

The results of forced vibrations are presented at the speed of movement V=60 km/h. The value $\lambda_к=\sqrt[4]{\frac{rb}{EI}}$ =0,0636 ((section 1-2), for section 4-5: λ_k=0.002, for section 3: λ_k=0.062. The functions S(λx), T (λx), V (λx), U(λx) are determined by formula (6) using tables for trigonometric and hyperbolic functions. **Table 2** shows the values of deflections, bending moments and transverse forces under static and dynamic action of force F ($F_{ст}$ =270 kN, F_{din}=270sinθt, where θ is the frequency of forced vibrations, at the speed of movement of 60 km/h θ=65.41 sec^{-1}).

Table 2
Deflections m, bending moments kNm and transverse forces kN in sections of reinforced concrete sleepers under static and dynamic effects.

Section number	Deflections, 10^{-3} m	Bending moments kNm	Transverse forces kN
	Static impact		
1-2	10,91	19,30	0
4-5	12,15	-28,59	100,98 -14,18
3	11,72	5,48	-95,62
	Dynamic impact		
1-2	13,74	26,24	0
4-5	16,52	-38,88	137,33 -19,28
3	15,93	7,45	-130,04

From **Table 2** it can be seen that the dynamic coefficient is approximately μ_{din}=1,36.

Table 3 shows the values of maximum normal and shear stresses (Ϭx, kgf/cm^2, $\tau_{yx,}$, kgf/cm^2) in the sections of reinforced concrete sleepers.

Table 3
Values of maximum normal stresses Ϭx, kgf/cm^2

Number sections	Ϭx, kgf/cm^2 Statics	τ_{yx}, kgf/cm^2 Statics	Ϭx, kgf/cm^2 Dynamics	τ_{yx}, kgf/cm^2 Dynamics
1-2	74,43	0	101,22	0
4-5	277,41	22,4 -3,14	377,28	30,5 -4,3
3	49,69	23,8	67,78	32,4

According to the building codes of the Republic of Kazakhstan, the average compressive strength of B40 concrete, taking into account the variation coefficient of 13.5%, is 523.7 kgf/cm^2, bending strength is 349 kgf/cm^2, tensile strength is 48 kgf/cm2, and shear strength varies in the range from 10.2 to 61.2 kgf/cm^2.

Table 3 shows that the highest normal stresses are in section 4-5, the deflections in this section are also increased in comparison with the section in the middle of the sleeper span, and with an increase in load, cracks may appear on the outer surface. The safety factor for normal stresses is 1.39. The highest tangential stresses are in section 3, in this section, shifts in the direction of the y axis are possible, which can lead to an emergency situation when trains are moving. It should be noted that when calculating railway sleepers, shear deformation is often neglected, considering it small in comparison with bending deformation. As the results of this calculation show, the safety reserve for shear is quite small.

5 CONCLUSIONS

Summarizing the obtained results, the following conclusions can be drawn:

1. Using analytical methods, it is possible to identify and specify the dynamic reserve of strength and reliability of railway scales of railways at different speeds of movement and at different values of base rigidity. These results will allow predicting the behavior of sleepers at different values of weight and speed of the moving train.

2. Practice shows that failure to take into account dynamic effects when calculating railroad sleepers leads to the appearance of various defects. To enhance the bearing capacity and reliability, it is necessary to take into account all possible types of deformations and their stability.

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RESEARCH ARTICLE

ANALYSIS OF DEGRADATION MECHANISMS AND JUSTIFICATION OF REPAIR TECHNOLOGIES FOR CONCRETE HYDRAULIC STRUCTURES

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Abstract. *This study analyzes the mechanisms of damage and patterns of degradation in concrete hydraulic structures exposed to operational and environmental factors. A comprehensive analysis was conducted using literature data, field inspection results, and regulatory documents covering the period from 2015 to 2025. Structural–mechanical analysis and comparative evaluation of repair technologies were applied to systematize the findings and assess the efficiency and durability of different materials and methods. The main damage mechanisms were identified as cavitation, leaching of cement paste, reinforcement corrosion, and thermal fatigue. The use of ultra-high-performance fiber-reinforced concrete (UHPFRC) was found to reduce cavitation wear by 3-4 times, while bioconcrete enables partial self-healing of microcracks and increases the service life of structures by 25-40%. A classification of defects based on their type and depth of deterioration was developed, allowing for a rational selection of repair technology depending on operating conditions and damage characteristics. The scientific novelty of this research lies in the proposed systematic approach to assessing concrete degradation and in the justification of composite material applications for extending the service life of hydraulic structures.*

Keywords: *concrete structures, hydraulic structures, cracks, erosion, cavitation, corrosion, repair, injection technologies, fiber concrete, life cycle.*

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ГИДРОТЕХНИКАЛЫҚ ҒИМАРАТТАРЫНЫҢ БЕТОН ҚҰРЫЛЫМДАРЫН ЗАҚЫМДАНУ МЕХАНИЗМДЕРІН ТАЛДАУ ЖӘНЕ ҚАЛПЫНА КЕЛТІРУ ТЕХНОЛОГИЯЛАРЫН НЕГІЗДЕУ

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Аңдатпа. *Бетоннан жасалған гидротехникалық ғимараттарының құрылымдарына өндірістік және табиғи факторлардың әсерінен туындайтын зақымдану механизмдері мен деградация заңдылықтары зерттелді. 2015–2025 жылдар аралығындағы ғылыми әдебиеттер, далалық зерттеу нәтижелері және нормативтік құжаттар кешенді түрде талданды. Алынған нәтижелерді жүйелеу үшін құрылымдық-механикалық талдау әдістері және технологиялық шешімдердің тиімділігі мен ұзақмерзімділігін салыстыру тәсілдері қолданылды. Негізгі зақымдану механизмдері ретінде кавитация, цемент тасының шайылуы, арматураның коррозиясы және температуралық шаршау анықталды. Ультраберік талшықты бетонды (UHPFRC) қолдану кавитациялық тозу қарқындылығын 3-4 есеге дейін төмендететіні, ал биобетондарды пайдалану микрожарықтардың ішінара өздігінен бітелуін және құрылымдардың ұзақмерзімділігін 25-40 % арттыратыны дәлелденді. Зақым түрі мен тереңдігіне қарай ақаулардың жіктелуі жасалды, бұл пайдалану жағдайлары мен бұзылу сипатына сәйкес қалпына келтіру технологиясын негізді таңдауға мүмкіндік береді. Зерттеудің ғылыми жаңалығы бетонның деградациясын бағалаудың жүйелік тәсілін ұсыну мен гидротехникалық ғимараттардың қызмет ету мерзімін ұзартуға бағытталған композиттік материалдарды қолдану бағыттарын негіздеуде көрініс табады.*

Түйін сөздер: *бетон құрылымдары, су шаруашылығы ғимараттары, жарықшақтар, эрозия, кавитация, коррозия, жөндеу, инъекциялық технологиялар, талшықты бетон, өмірлік цикл.*

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НАУЧНАЯ СТАТЬЯ

АНАЛИЗ МЕХАНИЗМОВ РАЗРУШЕНИЯ И ОБОСНОВАНИЕ ТЕХНОЛОГИЙ ВОССТАНОВЛЕНИЯ БЕТОННЫХ КОНСТРУКЦИЙ ГИДРОТЕХНИЧЕСКИХ СООРУЖЕНИЙ

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Аннотация. *Исследованы механизмы разрушения и закономерности деградации бетонных конструкций гидротехнических сооружений под воздействием эксплуатационных и природных факторов. Проведён комплексный анализ литературных данных, результатов полевых обследований и нормативных документов за период 2015–2025 гг. Для систематизации результатов применены методы структурно-механического анализа и сопоставления технологических решений по эффективности и долговечности. Установлено, что основными механизмами разрушения бетона являются кавитация, выщелачивание цементного камня, коррозия арматуры и термическая усталость. Применение ультравысокопрочных волокнистых бетонов (UHPFRC) снижает интенсивность кавитационного износа в 3-4 раза, тогда как использование биобетонов обеспечивает частичное самозалечивание микротрещин и повышение долговечности конструкций на 25-40 %. Разработана классификация дефектов по типу и глубине повреждения, что позволяет обоснованно выбирать технологию восстановления в зависимости от условий эксплуатации и характера разрушений. Научная новизна заключается в предложении системного подхода к оценке деградации бетона и обосновании направлений применения композитных материалов для продления ресурса гидротехнических сооружений.*

Ключевые слова: *бетонные конструкции, гидротехнические сооружения, трещины, эрозия, кавитация, коррозия, ремонт, инъекционные технологии, фибробетон, жизненный цикл.*

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CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

During the preparation of this manuscript, the authors used artificial intelligence tools (ChatGPT) solely for editorial assistance, such as improving phrasing and checking grammar, spelling, and punctuation. All ideas, interpretations, and conclusions are the responsibility of the authors, who take full accountability for the content of the article.

АЛҒЫС/ҚАРЖЫЛАНДЫРУ КӨЗІ

Зерттеу Қазақстан Республикасы Ғылым және жоғары білім министрлігінің Ғылым комитетінің қаржылық қолдауымен № AP23487624 ғылыми жоба аясында орындалды.

МҮДДЕЛЕР ҚАҚТЫҒЫСЫ

Авторлар мүдделер қақтығысы жоқ деп мәлімдейді.

Мақаланы дайындау барысында авторлар жасанды интеллект құралдарын (ChatGPT) тек редакциялық көмек мақсатында пайдаланды: тұжырымдарды жетілдіру, грамматикалық, орфографиялық және тыныс белгілеріндегі қателерді тексеру үшін. Барлық идеялар, интерпретациялар мен қорытындылар авторларға тиесілі, және олар мақаланың мазмұнына толық жауапты.

БЛАГОДАРНОСТИ/ИСТОЧНИК ФИНАНСИРОВАНИЯ

Исследование выполнено при финансовой поддержке Комитета науки Министерства науки и высшего образования Республики Казахстан в рамках научного проекта № AP23487624.

КОНФЛИКТ ИНТЕРЕСОВ

Авторы заявляют, что конфликта интересов нет.

При подготовке рукописи авторы использовали инструменты искусственного интеллекта (ChatGPT) исключительно для редакторской поддержки: корректировки формулировок, проверки грамматических, орфографических и пунктуационных ошибок. Все идеи, интерпретации и выводы принадлежат авторам, которые несут полную ответственность за содержание статьи.

1 INTRODUCTION

The reliability and durability of hydraulic structures largely depend on the technical condition of their concrete components, which are continuously exposed to aggressive factors such as cyclic freezing and thawing, mechanical abrasion caused by water flow, cavitation, chemical degradation, and reinforcement corrosion.

Operational experience of hydraulic engineering structures shows that the most common defects include cracking, spalling and destruction of the concrete protective layer, cavitation damage, and corrosion processes that compromise the integrity of the structures. The presence of such defects not only reduces performance characteristics but also leads to significant maintenance and repair costs.

Methods for the rehabilitation of concrete structures, actively developed during the period 2015–2025, include both traditional approaches (such as the use of cement-based and polymer materials) and innovative technologies based on ultra-high-performance fiber-reinforced concrete (UHPFRC), injection mixtures, bio-concrete, and integrated protective systems **(Lampropoulos et al., 2023)**. The analysis of published studies revealed the absence of a systematic framework that links the mechanisms of concrete degradation with the selection of appropriate repair technologies depending on the nature of the damage **(Rakhimov et al., 2025)**.

The object of the research is the concrete structures of hydraulic engineering facilities, while the subject is the processes of their degradation and restoration using modern materials and technologies **(Sennikov et al., 2014)**.

The aim of the study is to develop an analytical framework for selecting and substantiating effective rehabilitation methods for concrete structures, ensuring improved durability and operational reliability.

2 LITERATURE REVIEW

The durability of concrete structures in hydraulic engineering facilities has been the subject of intensive research due to their operation under harsh environmental conditions, which necessitates the development of advanced repair strategies.

A bibliometric analysis for the period 2015-2025 revealed that scientific studies on concrete used in hydraulic structures are concentrated around five major thematic areas. The most actively developing topics are related to improving the strength and crack resistance of concrete, reflecting a sustained interest in issues of mechanical degradation and cavitation erosion. At the same time, there has been a noticeable increase in research focused on self-healing concretes and biotechnological approaches, which form a new direction in the study of material durability.

In parallel, integration with ultra-high-performance composite (UHPFRC) technologies – used for the repair and strengthening of hydraulic structures – has been intensifying. Numerical modeling of degradation processes and service-life prediction under fluctuating moisture and temperature conditions remain less developed areas, defining the prospects for further research. Thus, the results of bibliometric mapping confirm a gradual shift in research focus from the identification of damage to the development of adaptive and self-healing materials aimed at extending the service life of hydraulic engineering structures.

The results of the bibliometric analysis presented in **Figure 1** made it possible to identify the main directions of research development in the field of repair and protection of concrete structures in hydraulic engineering facilities for the period 2015–2025. The visualization revealed that the largest publication clusters are associated with improving the strength and crack resistance of concrete, the development of high-performance composites (UHPFRC), and biotechnological approaches to self-healing concrete. In addition, there is a consistent interest in topics related to electrochemical protection of reinforcement and modeling of degradation processes.

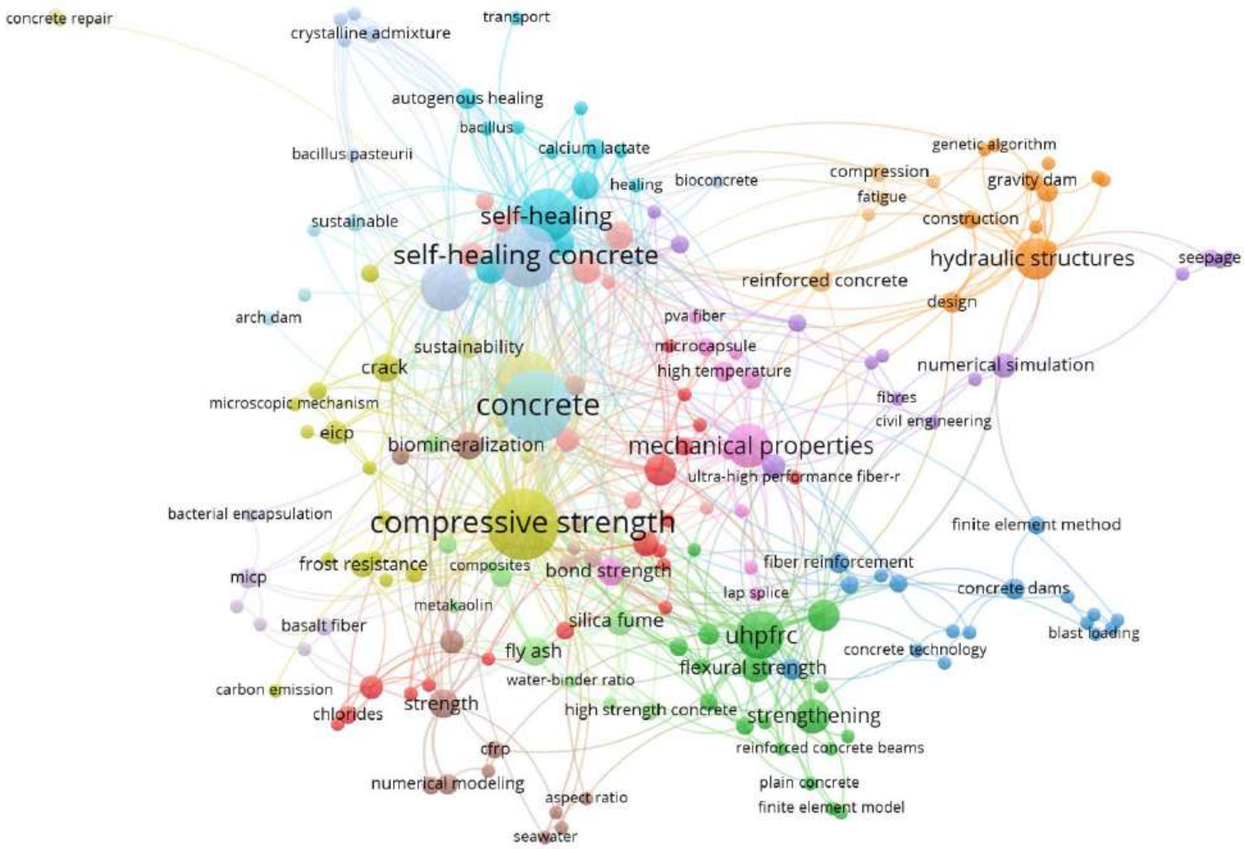

Figure 1 – Visualization of research topics on concretes for hydraulic structures (constructed in VOSviewer based on Lens.org data for 2015–2025). (author's material)

Thus, the results of the mapping served as the basis for identifying four key research areas presented below, each reflecting the current vector of scientific inquiry and practical solutions aimed at extending the service life and improving the protection of concrete structures in hydraulic engineering facilities.

1. *Application of high-performance composites.* One of the most effective materials for repairing areas exposed to intensive abrasive wear and high mechanical loads is ultra-high-performance fiber-reinforced concrete (UHPFRC). According to the study by **Yoo & Banthia (2022)**, the mechanical properties of UHPFRC are determined by the combination of curing conditions and fiber reinforcement parameters. Heat treatment accelerates hydration processes and promotes the formation of a dense cement matrix, while the use of deformed or elongated steel fibers enhances crack resistance and fracture energy. The selection of such technological parameters during mix design allows UHPFRC to be adapted to the specific operating conditions characteristic of hydraulic engineering structures.

2. *Crack repair and sealing.* The restoration of the integrity of concrete structures requires the use of materials capable not only of effectively filling cracks but also of ensuring long-term sealing performance, particularly under conditions of high humidity and chemical aggression. A study **(Li et al. 2022)** showed that the introduction of microcapsules containing an epoxy resin curing agent into the cement composition contributes to the restoration of strength and sealing of cracks, especially when exposed to various curing conditions. Biocementation, as one of the methods of microbial sealing, also shows high efficiency in restoring the waterproofing of concrete structures **(Cardoso et al. 2024)**. The presence of moisture on the concrete surface significantly reduces the adhesion strength with epoxy resins, which emphasises the need for thorough preparation of the substrate and the selection of moisture-resistant compounds when repairing structures in a humid environment **(Szewczak and Lagod 2022)**.

3. *Long-term corrosion protection.* Reinforcement corrosion remains the primary mechanism of reinforced concrete deterioration. For the protection of already damaged structures, the review by **Hu et al. 2022; Javeed et al. 2024** discusses electrochemical methods, particularly cathodic protection (CP) and electrochemical chloride extraction (ECE), as effective therapeutic solutions. CP systems, including configurations using carbon fiber-reinforced polymer (CFRP) as an anode, are capable of significantly slowing down corrosion progression.

4. *Self-healing ("smart") materials in construction.* One of the most actively developing areas of materials science is the creation of concretes capable of autonomous crack repair, thereby reducing maintenance costs and improving structural longevity.

The most thoroughly studied and experimentally validated mechanism of concrete self-healing is the biotechnological approach, which involves incorporating spores of *Bacillus* bacteria into the cement matrix **(Javeed et al. 2024)**. Upon contact of water with a crack, the microorganisms become active and initiate the process of bio-induced calcium carbonate ($CaCO_3$) precipitation, which restores the integrity of the concrete structure. This bio-induced self-healing mechanism transforms concrete from a passive structural material into an active, self-regulating system capable of autonomously responding to damage and extending the service life of hydraulic engineering structures. The use of bio-concretes offers promising prospects for the development of infrastructure with enhanced durability and reduced maintenance requirements.

3 MATERIALS AND METHODS

This study employed methods of systematic analysis and comparative evaluation of data on the mechanisms of degradation and repair technologies for concrete structures of hydraulic engineering facilities.

3.1. Data collection and analysis

The information base of the study was formed through an analysis of scientific publications, regulatory and technical documentation, and reports on the practical application of repair technologies.

The search for relevant sources was conducted in international and Russian scientometric databases – *Scopus*, *Web of Science*, *eLibrary*, and *Google Scholar* – covering the period from 2015 to 2024. The key search queries included: "repair of hydraulic concrete structures," "concrete durability," "reinforcement corrosion," "crack injection," "ultra-high-performance fiber-reinforced concrete (UHPFRC)," "electrochemical protection of concrete," and "bio-concrete." Additionally, current regulatory standards (GOST, SP) and real-world case studies of hydraulic structure repairs – including those implemented in the Republic of Kazakhstan, were analyzed.

3.2. Development of the classification framework

To systematize and further analyze the collected data, a two-level analytical framework was developed and applied.

1. Classification of degradation mechanisms **(Golewski, 2023)**. All defects were grouped into four main categories according to their origin and nature:

- Physico-mechanical degradation;
- Chemical degradation;
- Corrosion of reinforcement;
- Biogenic and microbiological degradation.

2. Systematization of repair methods.

Repair technologies were categorized in accordance with the above classification of damages they are intended to address. The main groups of methods include injection techniques, repair mortars (including polymer-cement compositions), protective systems based on UHPFRC, multilayer chemical-resistant coatings, electrochemical protection methods, and biotechnological approaches.

3.3. Evaluation criteria

The comparative analysis of the effectiveness of repair technologies was carried out based on three key criteria identified from the literature review:

1. Technical efficiency: The ability of the method to eliminate defects and restore the operational characteristics of the structure (e.g., strength and water tightness).
2. Durability: The predicted service life of the repaired area until the recurrence of damage, estimated from accelerated tests and practical field data.
3. Economic feasibility: The life-cycle cost evaluation of repair technologies using the *Lifecycle Cost Index (LCCI)*, which accounts for initial expenses as well as the frequency and cost of subsequent repair cycles.

The results obtained from the application of these methods – including the detailed analysis of degradation mechanisms, descriptions of repair technologies, and their comparative performance – are presented in the following section.

4 RESULTS AND DISCUSSION

4.1. Classification and Characteristics of the Main Types of Degradation

Based on the analysis of published research and practical case studies, a classification of the principal degradation mechanisms of concrete structures in hydraulic engineering facilities was developed. Grouping the damage types according to their nature and origin allows for a systematic approach to diagnostics and represents the first step in selecting an appropriate repair strategy **(Figure 2)**. The main categories include.

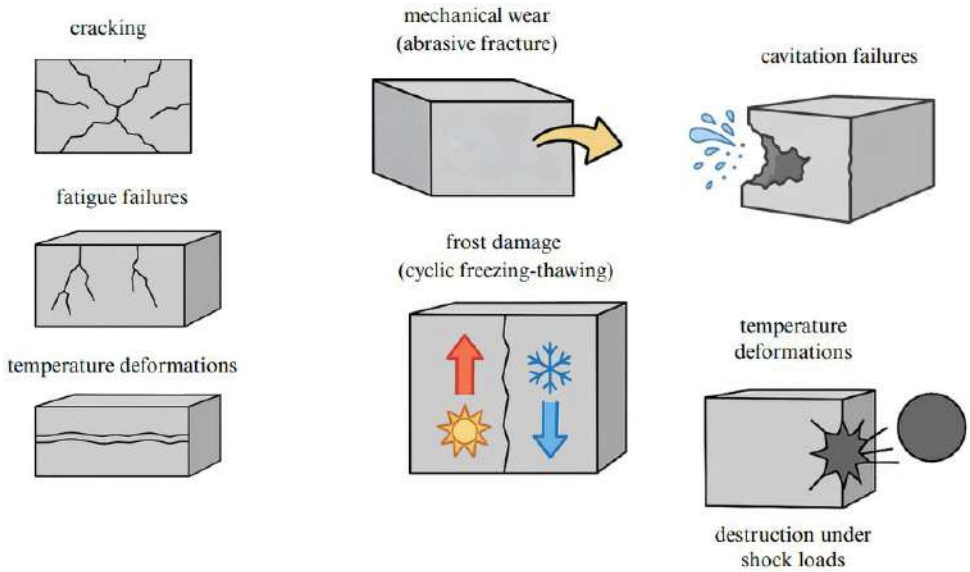

Figure 2 – Visualization of the types of physico-mechanical degradation of concrete structures (author's material)

4.1.1. Physico-mechanical degradation

This group comprises damage caused by external mechanical and climatic effects. The main types are as follows:

- Crack formation resulting from thermal shrinkage and deformation, leading to the loss of monolithic integrity of the structure.
- Cavitation damage occurring in zones of high-velocity water flow, where the collapse of vapor bubbles generates impact loads and localized surface destruction.
- Abrasive wear in areas where concrete is exposed to contact with solid particles carried by water (sediments) or with ice.

Enhancement of the abrasion resistance of concrete can be achieved through modification of its structure using surface-active agents, which promote a more uniform distribution of the cement matrix and reduce material porosity. Experimental data by **Moldamuratov et al. (2023)** confirm that the combined use of such additives with controlled water-to-cement ratios significantly improves the wear resistance of hydraulic concretes under turbulent water flow conditions.

4.1.2. Chemical degradation

This category encompasses the deterioration processes of the cement matrix caused by exposure to aggressive chemical agents, leading to a loss of strength and structural integrity **(Figure 3)**. The main types include:

- Leaching: Dissolution and removal of calcium hydroxide $Ca(OH)_2$ by soft water, which increases porosity and decreases the density of concrete.
- Acid corrosion: Destruction of cement matrix components upon contact with acids (e.g., H_2SO_4) formed as a result of industrial emissions or biogenic processes.
- Corrosion caused by aggressive gases: The impact of atmospheric gases (CO_2, SO_2, HCl), which dissolve in water to form acids that chemically attack the concrete.
- Sulfate attack: Interaction of sulfate ions (SO_4^{2-}) from groundwater or industrial environments with the aluminate phases of cement, resulting in the formation of expansive products (ettringite) and the development of internal stresses.

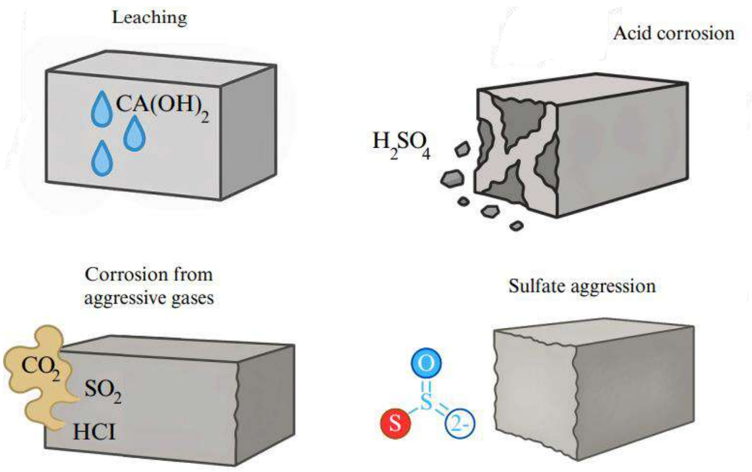

Figure 3 – Types of chemical degradation in concrete structures (author's material)

4.1.3. Corrosion-Induced Damage of Reinforcement

Reinforcement corrosion is one of the most critical types of deterioration in reinforced concrete structures, as it directly affects the structural load-bearing framework. The process is initiated by the ingress of moisture, CO_2, and chlorides into the concrete, which destroy the passive oxide film on the steel surface **(Figure 4)**.

- Carbonation corrosion: Caused by the penetration of carbon dioxide, which lowers the pH of the concrete to a level at which the passive protective film on the reinforcement becomes unstable and breaks down.
- Chloride-induced corrosion: Localized breakdown of the passive film due to chloride ions, leading to severe pitting corrosion even under high pH conditions.
- Delamination of the protective layer: Corrosion products (rust) have a volume 2-6 times greater than that of the original metal. The resulting internal pressure causes cracking and delamination of the concrete cover.

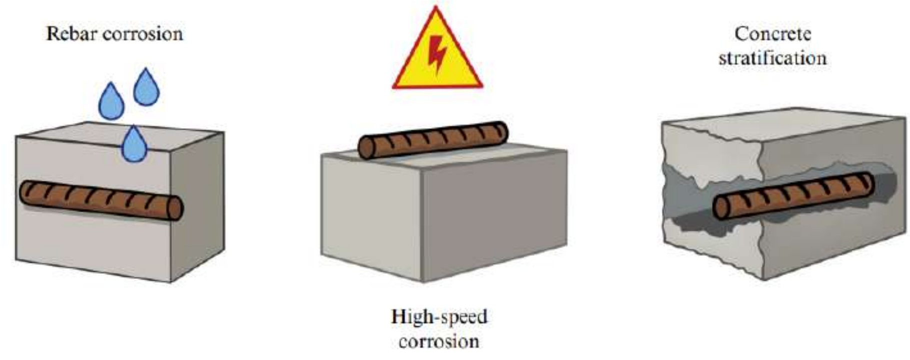

Figure 4 – Visualization of corrosion mechanisms affecting reinforcement in concrete structures (author's material)

4.1.4. Biogenic and Microbiological Deterioration

These are complex degradation processes caused by the activity of microorganisms such as algae, fungi, bacteria, and lichens. Biogenic agents not only induce local pH changes and moisture accumulation but also produce aggressive organic and inorganic acids. In particular, sulfur-oxidizing bacteria are capable of converting elemental sulfur into sulfuric acid (H_2SO_4), which accelerates the corrosion of the cement matrix **(Figure 5)**.

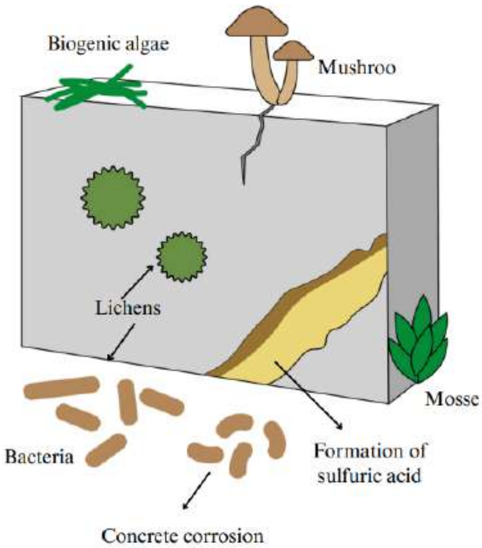

Figure 5 – Biogenic and microbiological impact on a concrete structure (author's material)

The presented classification indicates that concrete damage rarely occurs due to a single cause. A synergistic effect of multiple mechanisms is often observed – for example, cracks resulting from thermal deformation (a physical factor) can facilitate the ingress of sulfates (a chemical factor) and chlorides to the reinforcement (a corrosion factor). Therefore, an effective repair strategy should aim not only to eliminate the visible defect but also to mitigate the primary and accompanying mechanisms of deterioration **(Sun et al., 2022; Hu et al., 2024)**.

4.2. Systematization of Damage Mechanisms and Selection of Appropriate Repair Technologies

The analysis made it possible to generalize and structure the available data on concrete degradation in hydraulic structures, identifying four main groups of damage: physical–mechanical, chemical, corrosion-related, and biogenic. The results demonstrate that for each damage type, there exists a hierarchy of repair technologies with proven effectiveness. As shown in the following sections, the choice of an optimal solution depends not only on the nature of the defect but also on its scale and the required service life of the repaired structure.

4.3. Comparative Analysis of Restoration Technologies

4.3.1. Repair of Physical–Mechanical Damage: From Injection to UHPFRC

For the restoration of cracks, the most versatile method is injection grouting **(Tanyildizi et al., 2022) (Figure 6)**.

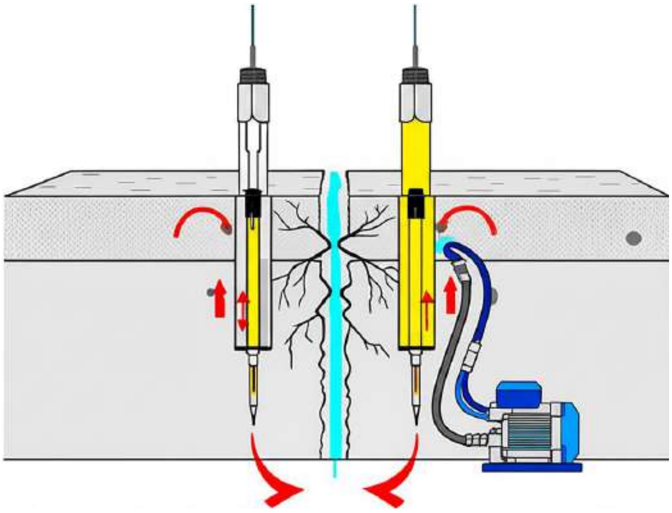

Figure 6 – Schematic representation of the crack injection technology (author's material).

The analysis revealed that the choice between epoxy and polyurethane resins depends on the intended purpose: epoxy resins provide structural bonding and restoration of load-bearing capacity, while hydroactive polyurethanes are indispensable for sealing active and water-leaking cracks due to their elasticity and expansive properties **(Chen et al., 2024) (Figure 7)**.

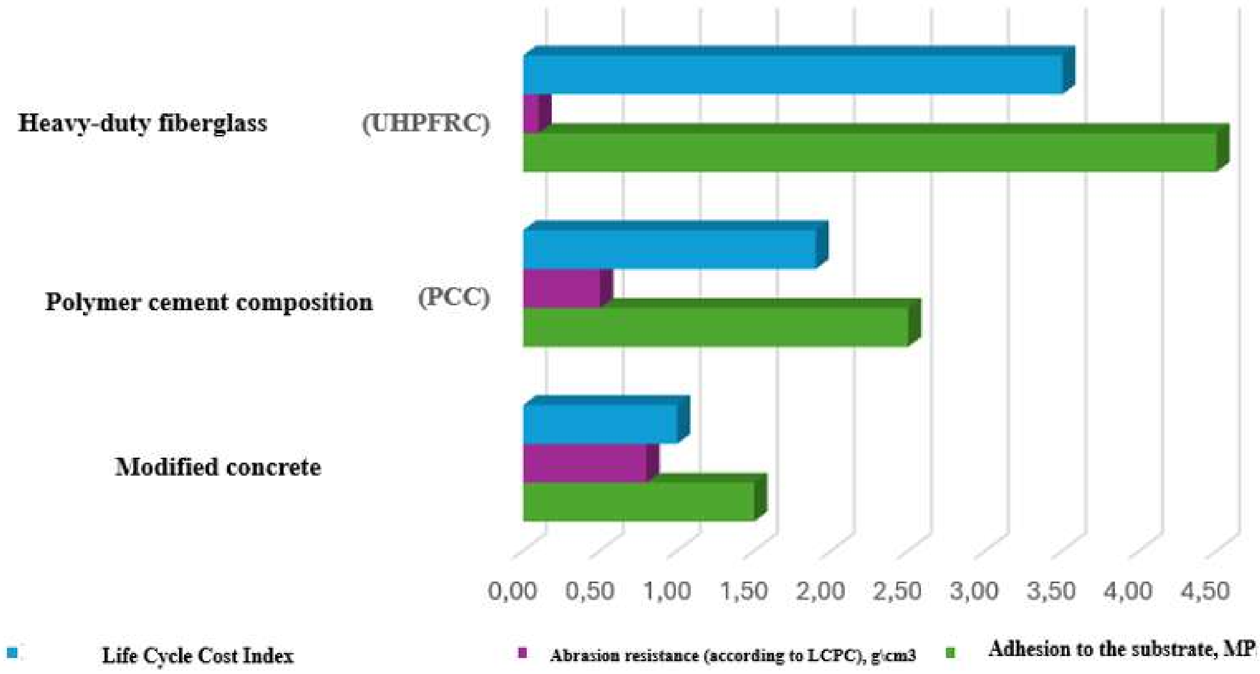

Figure 7 – Comparison of repair materials for concrete based on durability, adhesion, and cost efficiency indicators (author's material)

Ultra-high-performance fiber-reinforced concrete (UHPFRC) significantly surpasses both materials in all evaluated parameters **(Huang et al., 2022)**. Its compressive strength reaches 150–200

MPa, adhesion exceeds 4.0 MPa, and abrasion loss is less than 0.2 g/cm². The combination of high mechanical strength, superior adhesion, and extremely low wear ensures exceptional durability and operational reliability, even under the harsh conditions typical of hydraulic structures **(Zhakipbayev et al., 2025)**. The use of UHPFRC represents a technically sound solution for highly loaded areas that require maximum abrasion resistance and structural integrity.

Experimental data **(Moldamuratov et al., 2023)** confirm that the wear resistance of hydraulic concretes depends strongly on the regulation of the water-to-cement ratio and the type of surface-active agent (surfactant) used, which is consistent with the results presented in **Table 1**.

Table 1
Comparative characteristics of modern repair materials for wear zones

Characteristic	Modified concrete (as per GOST requirements)	Polymer cement composition (PCC)	Ultra-High-Performance Fiber-Reinforced Concrete (UHPFRC)
Compressive strength, MPa	50 – 60	60 – 80	150 – 200
Adhesion to the substrate, MPa	1.5 – 2.0	2.5 – 3.5	> 4.0
Abrasion resistance (LCPC), g/cm2	0.8 – 1.0	0.4 – 0.7	< 0.2
Cavitation resistance (relative)	Loq	Medium	Super High
Lifecycle Cost Index (LCCI), a.u.*	1.0	1.8 – 2.5	3.0 – 4.5

Note: The Lifecycle Cost Index (LCCI) takes into account not only the initial material cost but also its durability, as well as the frequency and cost of maintenance and repair intervals. Despite the high initial cost of UHPFRC, its use can be economically justified in critical structural zones due to the substantial increase in service life.

When analyzing abrasive wear and cavitation, comparative data indicate the technological advantage of next-generation composite materials. Polymer-cement composites (PCC) demonstrate significantly higher adhesion and wear resistance compared to conventional concrete **(Zuhair Al-Jaberi et al., 2022) (Figure 8)**.

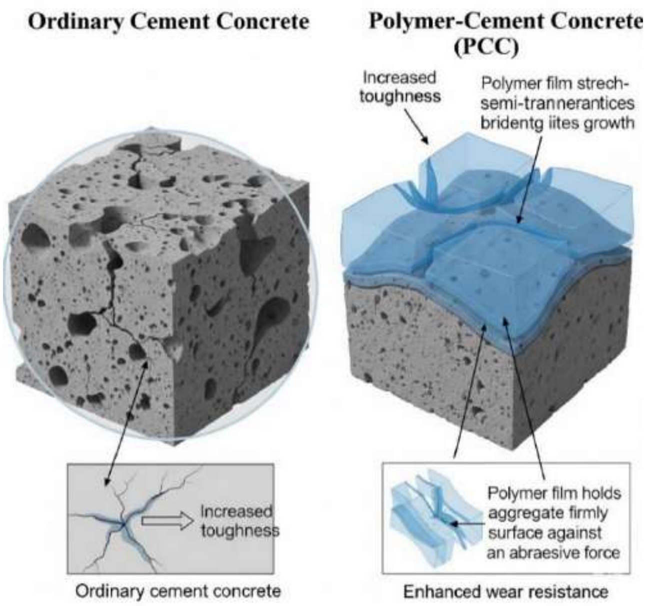

Figure 8 – Comparison of the microstructure of ordinary cement concrete and polymer-cement concrete (author’s material).

However, a qualitative leap in performance is achieved through the use of ultra-high-performance fiber-reinforced concrete (UHPFRC). Its resistance to abrasion and cavitation –

exceeding that of conventional concretes by a factor of 8-12 – is attributed to the synergistic combination of an ultra-dense matrix and the micro-reinforcing effect of steel fibers, which prevent aggregate spalling under the impact of high-velocity water flow **(Bandara et al., 2023)**.

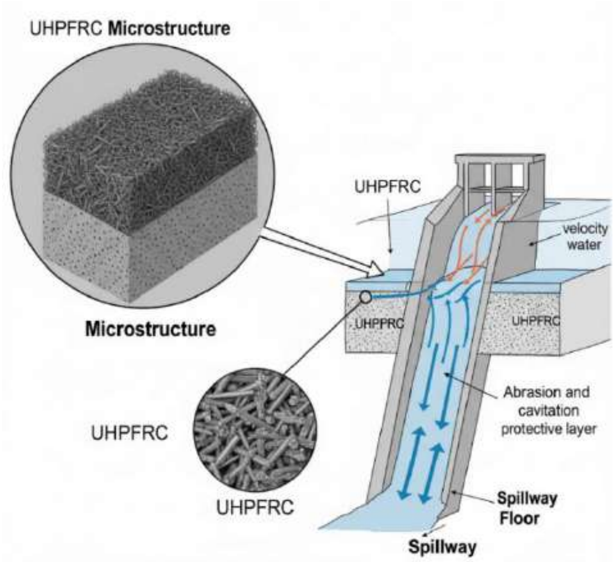

Figure 9 – Microstructure and application of ultra-high-performance fiber-reinforced concrete (UHPFRC) for the protection of hydraulic structures (author's material).

Microstructural analysis of cement composites **(Kabdushev et al., 2023)** confirms that the density and uniformity of the cement matrix are directly correlated with resistance to cavitation wear and crack formation, which aligns with the observed performance advantages of UHPFRC illustrated in **Figure 9**.

The high Lifecycle Cost Index (LCCI) of UHPFRC, presented in Table 1, often serves as a barrier to its widespread application. However, our analysis demonstrates that for critical zones of hydraulic structures (such as stilling basins and spillway aprons), where the cost of repeated repairs and equipment downtime is extremely high, the initial investment in UHPFRC is economically justified due to a substantial extension of the maintenance interval (from 3-5 years to 15-20 years).

4.3.2. Protection against chemical and biogenic aggression

The analysis of protection methods against chemical corrosion confirms that the most reliable solution is the formation of a multi-layer barrier system **(Figure 10)**.

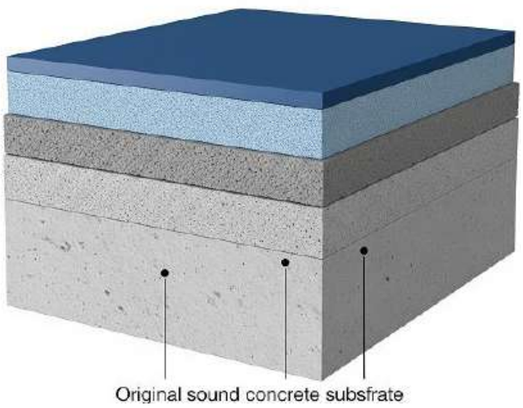

Figure 10 – System of concrete protection against chemical corrosion (author's material).

The use of specialized sulfate-resistant or calcium aluminate cements for repair, followed by the application of a final hybrid polymer coating, provides comprehensive protection against leaching, as well as acidic and sulfate attack **(Moldamuratov et al., 2022)**.

In the context of biogenic deterioration, alongside traditional rehabilitation methods, an actively developing approach involves the use of self-healing concrete, which ensures autogenous crack sealing and enhances the durability and service life of hydraulic concrete structures **(Osta & Mukhtar, 2024)**.

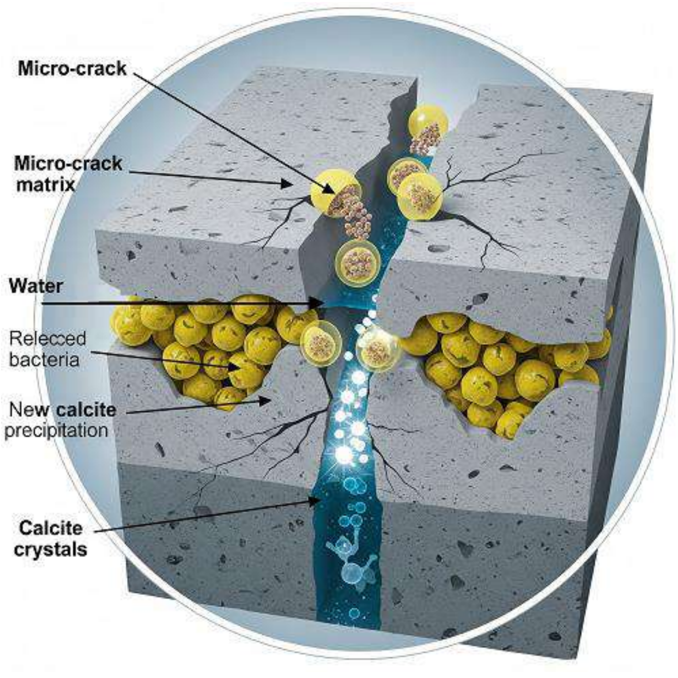

Figure 11 – Principle of bio-concrete operation (author's material).

The mechanism illustrated in **Figure 11**, where encapsulated bacteria are activated upon crack formation and produce calcium carbonate ($CaCO_3$), represents a transition from passive repair to an intelligent, autonomous system. According to recent studies, this technology is capable of sealing cracks up to 0.8 mm wide, marking a breakthrough in maintaining the watertightness of concrete structures **(Chaolin Fang & Varenyam Achal, 2023)**.

4.3.3. Long-Term Protection of Reinforcement Against Corrosion

The service life prediction of repair systems, presented in **Figure 12**, is one of the most illustrative results characterizing the behavior of reinforced concrete during restoration. The analysis of the graph indicates the low efficiency of localized repair strategies (Curve A). This behavior is explained by the incipient anode effect: after repairing a small area, a highly alkaline environment is created, turning it into a cathode, while the adjacent zones of old chloride-contaminated concrete become anodes, leading to accelerated corrosion. Complete removal of the contaminated concrete (Curve B) provides a longer, though still time-limited, improvement in durability **(Saqif et al., 2022)**.

Only the use of active protection systems, in particular embedded galvanic anodes (Curve C), ensures that the reinforcement remains in a passive state for a predicted period of 15–20 years **(Jakiyayev et al., 2021)**. The anode corrodes instead of the steel reinforcement, thereby providing cathodic protection **(Harahap et al., 2023)**.

The results of the service life analysis emphasize the need to reconsider existing repair approaches for reinforced concrete hydraulic structures. Instead of performing cyclic local repairs every 3–5 years, it is more rational to implement electrochemical cathodic protection systems, especially under aggressive environmental conditions.

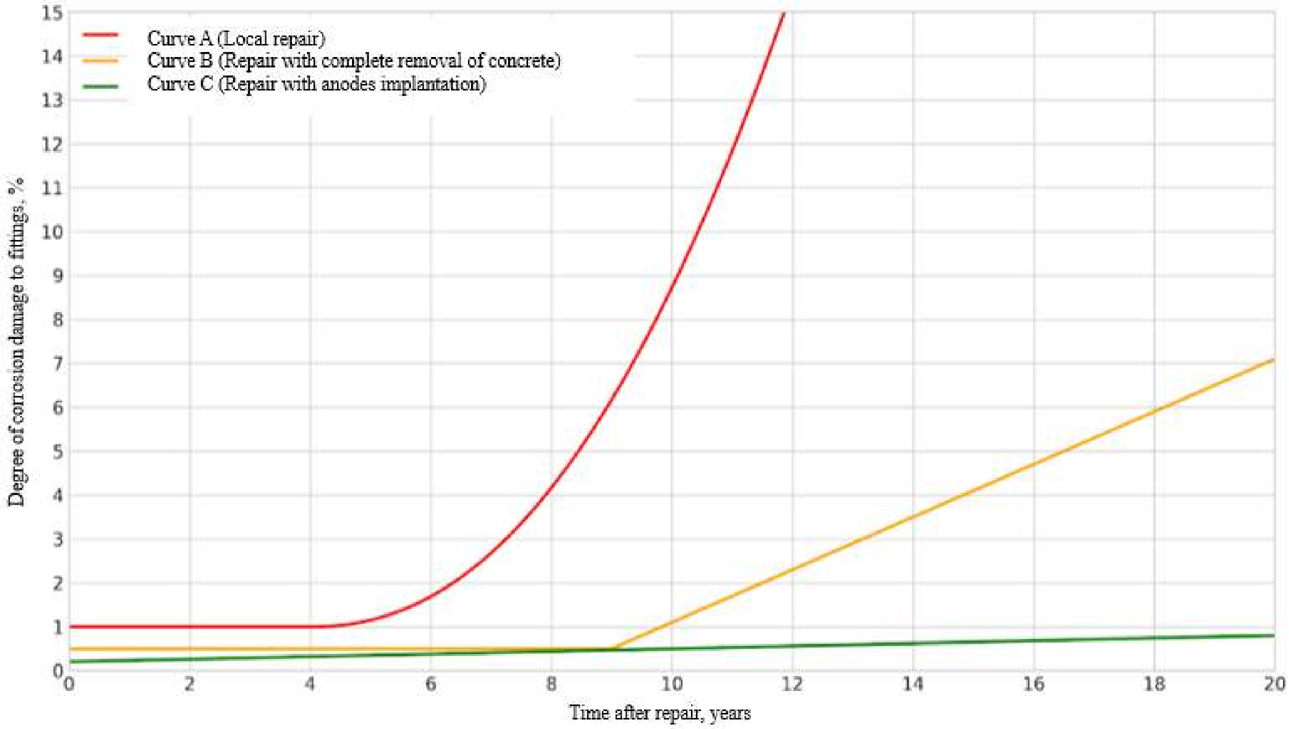

Figure 12 – Predicted service life of repairs under different reinforcement protection strategies (author's material)

4.4. Discussion in the Context of Kazakhstan's Conditions

The practical implementation of the discussed technologies at hydraulic facilities in Kazakhstan, such as the Kirov Reservoir and the Aktobe Hydraulic Complex – provides an opportunity to specify and validate the findings. The severely continental climate of Kazakhstan, characterized by large annual and diurnal temperature variations (freeze-thaw cycles), imposes increased requirements on the thermal compatibility and frost resistance of repair materials (F300 and above).

Our analysis showed that the successful use of polyurethane injection resins at the Aktobe Hydraulic Complex for joint sealing confirms their effectiveness under active deformation conditions. At the same time, operational experience demonstrates that for the repair of abrasion zones in spillway structures, the most wear- and frost-resistant materials, such as UHPFRC, should be preferred – even despite their higher initial cost – since traditional concretes require repeated repairs every 5-7 seasons.

Thus, for the conditions of Kazakhstan, it is necessary to adapt international experience: the selection of technologies should be based not only on the type of defect, but also on a comprehensive analysis of climatic loads and long-term economic efficiency. Further research focused on the development and testing of repair mixtures optimized for the specific operating conditions of hydraulic structures in the region appears to be highly relevant.

Comparative analysis of the accumulated repair cost using traditional concrete and UHPFRC. The **Figure 13** demonstrates the break-even point (approximately 12 years), after which the high initial cost of UHPFRC is compensated by the elimination of frequent repair needs, typical for traditional materials under the climatic conditions of Kazakhstan.

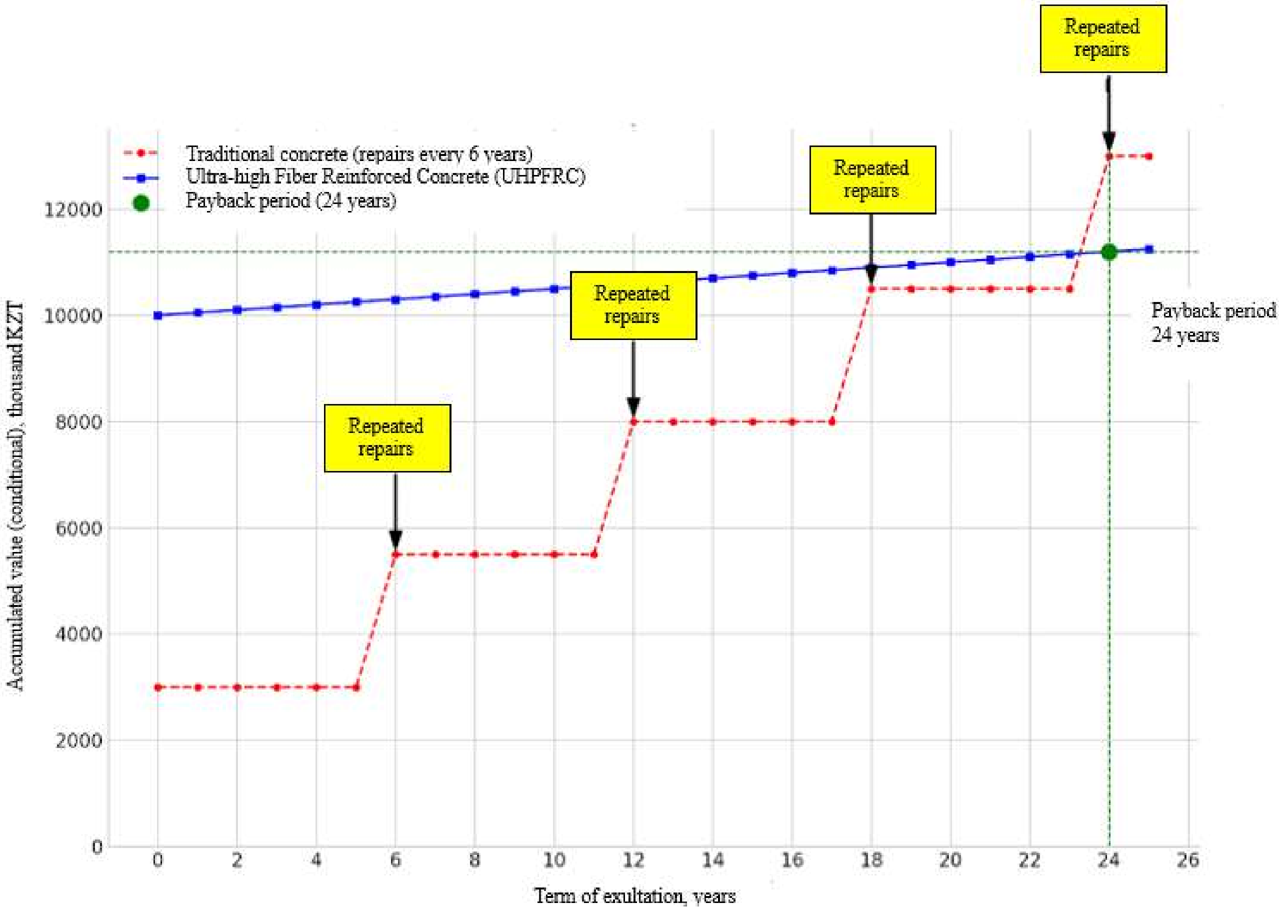

Figure 13 – Comparative analysis of repair technology efficiency (author's material).

5 CONCLUSIONS

The review and analysis conducted in this study made it possible to systematize the main mechanisms of concrete degradation in hydraulic structures and to identify modern technologies for their restoration. The key findings of the research are as follows:

1. It has been established that the degradation processes in hydraulic concrete structures are synergistic in nature: primary physico-mechanical damages (e.g., cracking) critically accelerate secondary chemical and corrosion mechanisms. This confirms the inefficiency of local repairs when the root cause is not addressed.

2. Comparative analysis revealed the absence of a universal repair solution and defined a clear hierarchy of applicable technologies. The optimal choice depends on the dominant degradation mechanism:

- UHPFRC for zones of intensive abrasion.
- Elastic polyurethane injection resins for sealing active leakages.
- Electrochemical methods for long-term reinforcement protection.

3. Evaluation based on the lifecycle cost index (LCCI) confirmed that, despite their higher initial cost, innovative materials (such as UHPFRC) and technologies (such as galvanic anodes) are economically justified for repairing critical and hard-to-access areas of hydraulic structures, due to their significantly extended maintenance intervals.

4. Active electrochemical protection systems are the only approach that not only halts ongoing reinforcement corrosion, but also prevents its initiation in adjacent zones (the "incipient anode" effect), thereby ensuring maximum repair durability.

5. For the Republic of Kazakhstan, the primary challenge lies not in the direct adoption of foreign technologies, but in the development of adapted rehabilitation strategies.

These strategies must take into account the harsh continental climate (increased requirements for frost resistance and thermal compatibility of materials) and the specifics of the national regulatory framework.

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RESEARCH ARTICLE

ANALYSIS AND EVALUATION OF EXPERIMENTAL METHODS FOR DETERMINING THE STRENGTH OF CONCRETE

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Abstract. *The study presents an overview of several experimental techniques used to determine the strength and bearing capacity of concrete. During the research, special attention was paid to how the quality of the mix and curing conditions influence the reliability of the results. The experiments were carried out on cube, prism, and cylinder specimens that were tested at different stages of hardening. The obtained data helped to trace how the internal structure of concrete changes with time and to identify the factors that most strongly affect its load resistance. Compressive and flexural strengths were determined using three specimen types: cubes, prisms, and cylinders. Ten samples of each shape were produced and tested at different ages over a curing period of 180 days. These experiments allowed calculation of the coefficient of variation and tracking of strength development over time. Results showed that destructive testing provides dependable data on the mechanical response of concrete under load. The total specimen volume did not significantly influence strength; however, widening the cross-sectional area at the upper surface tended to reduce resistance and foster the formation of micro-cracks. Conversely, smaller sections demonstrated higher strength values and more stable variation coefficients. The findings also underline the limitations of relying solely on average strength indicators.*

Keywords: *prism, concrete, load, strength, bending, compression, standard deviation.*

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БЕТОННЫҢ БЕРІКТІГІН АНЫҚТАУДЫҢ ЭКСПЕРИМЕНТТІК ӘДІСТЕРІН ТАЛДАУ ЖӘНЕ БАҒАЛАУ

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Аңдатпа. *Мақалада бетонның беріктік қасиеттерін бағалау және оның жүктемені көтеру қабілетін анықтау әдістері қарастырылды. Эксперименттік сынақтар барысында әртүрлі формадағы үлгілердің сыну ерекшеліктері талданды. Зерттеудің маңызды бөлігі-бетон сапасын жүйелі бақылау. Себебі сенімді ақпарат жинау болашақта ғимараттар мен құрылымдық элементтердің беріктігін, сондай-ақ ұзақ мерзімді жұмыс қабілеттілігін қамтамасыз етеді. Сондықтан нақты жағдайда дұрыс әдісті таңдау, сонымен қатар бетонның ішкі құрылымына назар аудару аса өзекті міндет болып табылады. Зерттеудің негізгі мақсаты – материалдың сығылуға және иілуге беріктік көрсеткіштерін анықтау үшін сыну әдістерін қолдану болды. Осы мақсатта үш түрлі үлгі формасы дайындалды: куб, призма және цилиндр. Әр форма бойынша он данадан үлгілер әзірленіп, 180 күн бойы сынақтан өткізілді. Үлгілерге жүргізілген тәжірибелердің нәтижесінде вариациялық коэффициент есептелді, сондай-ақ уақыт өте келе беріктіктің өзгеруі бақыланды. Нәтижелер көрсеткендей, сындыруға негізделген әдістер бетонның механикалық қасиеттерін дәлірек бағалауға мүмкіндік береді. Ал бұзбайтын әдістер тек қосымша бақылау құралы ретінде тиімді, бірақ негізгі бағалау үшін жеткіліксіз. Тәжірибе бетон элементінің жалпы көлемі беріктікке айтарлықтай әсер етпейтінін дәлелдеді. Дегенмен, үлгінің жоғарғы кесім аймағының ұлғаюы беріктікті төмендетіп, микрожарықтардың пайда болуына ықпал етті. Керісінше, кішігірім қималар жоғары беріктік мәндерін көрсетіп, вариация коэффициентінің тұрақтылығын арттырды. Сонымен қатар, тек орташа деректерге сүйену қателіктерге алып келуі мүмкін. Әрбір конструкциялық элемент үшін жеке беріктік көрсеткіштерін таңдау – құрылымдық қауіпсіздікті қамтамасыз етудің маңызды шарты. Бұл ғылыми тұжырымдар құрылыс саласында сапаны арттыруға және инженерлік шешімдердің сенімділігін күшейтуге бағытталған.*

Түйін сөздер: *призма, бетон, жүктеме, беріктік, иілу, сығу, стандартты ауытқу.*

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НАУЧНАЯ СТАТЬЯ

АНАЛИЗ И ОЦЕНКА ЭКСПЕРИМЕНТАЛЬНЫХ МЕТОДОВ ОПРЕДЕЛЕНИЯ ПРОЧНОСТИ БЕТОНА

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Аннотация. *В этой статье проведен анализ методов характеристик прочности бетона и его несущей способности. Выполнен анализ испытанных образцов экспериментальным методом на разрушение. Важной частью данного исследования является контроль качества бетона, поскольку успех сбора информации по данному материалу несет в себе дальнейшую несущую способность элементов каркаса зданий и сооружений. Поэтому в наши дни очень важным является подбор правильного в конкретном случае метода экспериментального исследования, уделяя большое внимание структурной сетке бетона. Перед собой мы поставили цель провести экспериментальные разрушающие методы для выявления оценочного показателя прочностной характеристика данного материала на сжатие, а также на изгиб. Поэтому в первую очередь задача была в том, чтобы подготовить три формы образцов из куба, призмы и цилиндра. Затем по готовности были выполнен эксперимент разрушающего метода, выявление вариативного коэффициента. Были испытаны 10 видов образцов каждой формы на протяжении 180 дней влияния прочности бетона. По результату сделан вывод, что данный метод эксперимента помогают получить точные данные поведения прочности бетона и его дальнейшей эксплуатации строительной конструкции, причем, при любых возможных условиях, нежели метод неразрушающий, который использовать можно как дополнительный для контроля качества бетонной конструкции. Данный эксперимент показал, что объем конструкции элемента на прочность не влияет. Но подводя итоги выявилось, что если увеличить площадь на верхнем сечении, то снизится прочностные свойства бетона, соответственно и приведет к нежелательным микрофракциям. Повышение несущей способности бетона, коэффициент вариации прочности связано с небольшими сечениями испытываемых образцов.*

Ключевые слова: *призма, бетон, нагрузка, прочность, изгиб, сжатие, среднеквадратичное отклонение.*

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CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

The authors declare that no generative artificial intelligence technologies or AI-based tools were used in the preparation of this article.

АЛҒЫС / ҚАРЖЫЛАНДЫРУ КӨЗІ

Зерттеу жеке қаржыландыру көздерін пайдалана отырып жүргізілді.

МҮДДЕЛЕР ҚАҚТЫҒЫСЫ

Авторлар мүдделер қақтығысы жоқ деп мәлімдейді.

Авторлар мақаланы дайындау барысында генеративті жасанды интеллект технологиялары мен жасанды интеллектке негізделген технологияларды пайдаланбағанын мәлімдейді.

БЛАГОДАРНОСТИ/ИСТОЧНИК ФИНАНСИРОВАНИЯ

Исследование проводилось с использованием частных источников финансирования.

КОНФЛИКТ ИНТЕРЕСОВ

Авторы заявляют, что конфликта интересов нет.

Авторы заявляют о том, что при подготовке статьи не использовались технологии генеративного искусственного интеллекта и технологии, основанные на искусственном интеллекте.

1 INTRODUCTION

In modern construction practice, ensuring the reliability of reinforced concrete structures remains one of the most important engineering challenges. Although various national and international standards regulate the classification of concrete strength, the practical application of these methods still raises questions regarding their accuracy and comparability.

In our study, we focused on evaluating the actual strength of concrete using different specimen shapes and testing techniques. The experiments were performed at Vilnius Gediminas Technical University (VILNIUS TECH, Lithuania) with the use of a servo-hydraulic testing machine LVF5000 (capacity 5 MN, WALTER + BAI AG, Switzerland). The load was applied gradually under the control of DION 7 software, while all measurements were automatically recorded using the ALMEMO 5690-2 system.

Before fabricating the experimental reinforced concrete beams, we verified the quality of the mix and compliance of materials with technical standards to prevent premature failure. In this context, special attention was paid to the selection of aggregates and the control of curing conditions, since both directly affect the load-bearing performance of structural elements.

In practice, the strength of concrete represents its ability to resist external forces without visible damage or internal cracking. This property largely depends on the homogeneity of the mixture and the proportion between cement, water, and aggregates. Therefore, each batch must be tested to confirm that the material meets design requirements and provides sufficient safety margins for long-term use.

Taking these aspects into account, the current research aimed to analyze destructive testing methods for determining the compressive and flexural strength of concrete. Following the recommendations of the national standard ST RK ISO 1920-6-2009 “Testing of Concrete. Part 6. Sampling, preparation and testing of reinforced concrete frames,” destructive testing was selected as the main experimental approach, as it allows for the most accurate assessment of real mechanical behavior under load.

2 LITERATURE REVIEW

Research on concrete has been conducted for nearly a century, resulting in a substantial body of knowledge regarding the influence of concrete properties on the structural characteristics of construction projects. The experience of the Russian school of design has consolidated this knowledge, emphasizing the fundamental factors affecting concrete strength as well as its impact on the overall performance of structures.

Notable contributions have been made by authors such as **(Bazhenova Y.M. & Kolchunova V.I., 2005)**, who focused on the effects of the material’s structural form on the outcomes of destructive testing of concrete. Further insights were provided by **(Loganina V.I., 2014)** and **Krivenya S.M., 2018)**, whose work contributed to understanding the behavior of compacted concrete, highlighting the critical role of concrete strength in both bending and compression performance.

Research in Kazakhstan has been conducted taking into account the available raw material resources as well as the climatic conditions of the country. Studies by **(Lukpanova R. et al., 2021)** focused on the influence of concrete strength characteristics using cubic samples. The work of **(Begentayev M. et al., 2025)** addressed the assessment of compressive strength with the use of ash additives, providing results that highlight the impact of modern admixtures and their potential application in practical construction.

Experience shows that both Russian and Kazakh research has progressed from studying basic concrete strength characteristics to developing innovative models that consider the material’s structure and proper use, which have a significant effect on the overall load-bearing capacity of structures.

The primary objective today is to optimize the use of collected material data, taking into account the influence of sample shape and testing methods on concrete strength. This need has become the central focus of the present study, emphasizing the importance of accurate assessment methods to ensure both safety and durability in construction applications.

3 MATERIALS AND METHODS

At the laboratory of Vilnius Gediminas Technical University (VILNIUS TECH), samples of three types were prepared: cylinders, cubes, and prisms. Specifically, ten cylindrical samples with a diameter of Ø150 mm and a height of 300 mm were prepared, ten prism samples with a cross-section of 100×100×400 mm, and ten cubic samples measuring 150×150×150 mm.

The experimental-laboratory investigations were conducted in several stages: an examination of the current state of research has shown a lack of approaches for analyzing the strength of small-sized cylindrical and cubic specimens; the formulation of theoretical principles for evaluating concrete strength, grounded in the previously proposed failure model; cconducting multiple experimental investigations on the stress–strain behavior of concrete specimens, with variation of the key parameters influencing their strength; conducting experimental testing of concrete specimens.

The main concrete specimens in the form of cylinders and cubes were prepared in the laboratory of Vilnius Gediminas Technical University (VILNIUS TECH) using a concrete mixer, as shown in **Figures 1-5.**

Figure 1 – Concrete mixer unit (author’s materials)

Metallic collapsible molds were used for specimen preparation. The concrete mix was compacted using vibrators operating at a frequency of 2,500 semi-oscillations per minute with an amplitude of 0.45 mm. During the spring–summer period, specimens were prepared under natural curing conditions. The ambient air temperature during casting ranged from 15 to 19°C. Demolding was carried out 5-6 days after casting. Prior to testing, all specimens were stored in moist sawdust to maintain adequate humidity.

Figure 2– Concrete Mix Preparation (author's materials)

During the casting of concrete samples in the form of cylinders and cubes, special molding forms were used, as shown in Figure 3. Metal collapsible molds were employed to shape the samples. The concrete mixture was compacted using vibrators operating at a frequency of 2,500 half-cycles per minute with an amplitude of 0.45 mm. In the spring and summer season, samples were produced under conditions of natural curing. The ambient temperature during sample preparation averaged between 15 and 19°C. Demolding was performed 5–6 days after casting. Prior to testing, the samples were stored in moist sawdust.

Figure 3– Fabrication of Samples in the Form of Cylinders and Cubes (author's materials)

Figure 4 – Cylinder molding form (author's materials)

Figure 5 – Cube, prisms molding form (author's materials)

Concrete specimens of three types were prepared at the laboratory of Vilnius Gediminas Technical University (VILNIUS TECH) for experimental testing: ten cylinders (Ø150 × 300 mm), ten prisms (100×100×400 mm), and ten cubes (150×150×150 mm). Prior to testing, all specimens were cured for 28 days under standard laboratory conditions to ensure uniform hydration and strength development. Each sample was visually inspected for defects such as cracks, voids, or surface irregularities, and any specimens not meeting quality criteria were excluded from the study. Dimensional measurements and mass recording were performed to confirm conformity with the specified sizes, ensuring reliability and reproducibility of results.

During testing, the stress–strain behavior of each specimen was continuously recorded using precision sensors and data acquisition systems. Observations were made on crack initiation, propagation, and final failure modes, which were documented with photographs and video recordings. These data allowed detailed analysis of the mechanical behavior of concrete under destructive loading and provided a basis for evaluating the influence of specimen geometry on compressive and flexural strength.

All tests were conducted in triplicate for each type of specimen to ensure reproducibility and reliability of the results. The recorded data were processed to calculate key mechanical properties, including compressive strength for cylindrical and cubic specimens, and flexural strength for prism specimens.

Statistical analysis was applied to determine average values and standard deviations, providing a quantitative basis for comparing the performance of different specimen types and evaluating the effect of geometry on concrete behavior. In this case, we ensured conditions in which the control concrete samples were cured in chambers with automatic maintenance of optimal temperature and humidity, as shown in **Figures 6–9.**

Before beginning the fabrication of the experimental reinforced concrete beam for strength testing, it was essential to ensure that the future structure would comply with the standards and not fail prematurely. This required verifying the quality of the construction process and the choice of building materials. In this context, careful attention must be paid to the quality of the concrete mix, with its key parameter being the material's strength characteristics.

Figure 6 – Preparation of cylinder-shaped specimens (author's materials)

Figure 7 –Preparation of cube-shaped, prism-shaped specimens, cylinder-shaped specimens (author's materials)

Figure 8 – Preparation of cube-shaped, prism-shaped specimens (author's materials)

Figure 9 – General view of the molding forms with cast concrete specimens (author's materials)

At each stage of the experiments, particular attention was paid to controlling the dimensions and quality of the specimens, proper placement in the testing machines, and accurate recording of loads and deformations. Standard compression tests were applied for cylindrical and cubic specimens, while prism specimens underwent bending tests to evaluate their flexural strength.

Specimens were prepared for experimental studies to test compression, tension, and bending; the data are presented in **Table 1**.

Table 1

Experimentally investigated variants of control specimens (author's materials)

Type of Test	Specimen Shape	Linear Dimensions, mm
Compression and Tension Testing	Cubic	with dimensions 150×150×150 mm
	Cylindrical	Ø150, h=300 mm
Axial Tension Testing	Prismatic	with dimensions from 100x100x400 mm up to 300x300x1200 mm
	Cylindrical	Ø150, h=300 mm
Flexural Strength and Tension Test	Prismatic	with dimensions from 100×100×400 mm up to 300×300×1200 mm

Some prisms were kept moist for 2 days and then subjected to steam treatment according to the following procedure: the temperature was raised to 80 ° C over three hours, maintained for 8 hours, and then reduced to 6 °C over six hours. The concrete mix was designed to produce three strength classes: low strength (classes B15 and B25), medium strength (classes B30 and B40), and high strength (class above B50). The next stage of the study involved testing the samples for compressive and flexural strength using a specialized press machine located in the laboratory of Vilnius Gediminas Technical University (VILNIUS TECH), as shown in **Figure 10**.

Figure 10 – Strength tests on a specialized press machine in the laboratory of Vilnius Gediminas Technical University (VILNIUS TECH) (author's materials)

In the laboratory, the experimental analysis of concrete properties was performed using a hydraulic press. Cube- and cylinder-shaped specimens were placed under the press, and the load was gradually increased until failure occurred, as illustrated in **Figures 11-12.**

Metallic collapsible molds were used to produce the specimens. The concrete mix was compacted using vibrators with a frequency of 2,500 semi-oscillations per minute and an amplitude of 0.45 mm. During the spring-summer period, specimens were prepared for natural curing. During specimen preparation, the ambient air temperature ranged from 15 to 19° C. Demolding was performed 5-6 days after casting. Before testing, the specimens were stored in moist sawdust.

Figure 11 – Strength tests on the specialized press machine in the laboratory of Vilnius Gediminas Technical University (VILNIUS TECH) (author's materials)

Figure 12 – Strength tests conducted on a specialized press machine in the laboratory of Vilnius Gediminas Technical University (VILNIUS TECH) (author's materials)

Two Canon EOS 77D DSLR cameras equipped with Canon EF-S 18–135 mm lenses were mounted on tripods at a distance of 2000 mm from opposite faces of the beam to capture digital images. Camera settings included a shutter speed of 1/100 s, an aperture of f/4.0, a focal length of 24 mm, and an ISO sensitivity of 100. Images with a resolution of 6000×4000 pixels were captured at each 5 kN increment of applied load. The remote-control device was used to prevent unintended displacement of the cameras. The GOM Correlate software (GOM Metrology, Germany) was employed to monitor and visualize the tensile and compressive strength tests.

4 RESULTS AND DISCUSSIONS

At this stage of the work, we compared how the shape and size of the specimens affected the compressive strength of concrete. During testing, it became clear that even small differences in geometry can slightly change the load-bearing capacity. The results are summarized below and include both direct measurements and our own observations of fracture patterns. In general, smaller samples showed higher strength values, which agrees with similar laboratory findings reported in earlier studies. The ultimate compressive force values were recorded and documented in the concrete testing protocol, with corresponding load and strength measurements summarized in **Table 2**, as presented in the results section.

Table 2

Concrete Cube Compressive Strength Test from the Experimental Study Conducted on 05.05.2023 (Author's Materials)

05.05.2023											
								Age	**7**	**28.04.2023**	
Concrete Cube Compressive Strength Test											
1_cube			**2_cube**			**3_cube**			**4_cube**		
Dimension mm		**Mass, gr**	**Dimension mm**		**Mass, gr**	**Dimension mm**		**Mass, gr**	**Dimension mm**		**Mass, gr**
1	151,1	8053	1	154,01	8213	1	152,3	8102	1	152,57	7953
2	151,4	V_c, mm^3	2	153,58	V_c, mm^3	2	151,0	V_c, mm^3	2	151,51	V_c, mm^3
3	151,9	3487301	3	154,22	3534168	3	153,8	3472345	3	152,56	3457472
4	151,4	p, kg/m^3	4	156,47	p, kg/m^3	4	150,7	p, kg/m^3	4	151,31	p, kg/m^3
5	151,6	2309,2	5	151,82	2323,9	5	151,3	2333,3	5	150,64	2300,2
6	152,1	Load, kN	6	151,53	Load, kN	6	151,8	Load, kN	6	150,63	Load, kN
7	152,0	881,7	7	151,92	833,8	7	150,1	946,8	7	150,20	869,7
8	152,1	$R_{15\times15}$, MPa	8	151,86	$R_{15\times15}$, MPa	8	150,3	$R_{15\times15}$, MPa	8	150,22	$R_{15\times15}$, MPa
9	150,9	38,28	9	150,80	35,54	9	151,5	41,27	9	151,24	38,04
10	151,9	A_c, mm^2	10	150,96	A_c, mm^2	10	151,3	A_c, mm^2	10	151,32	A_c, mm^2
11	150,8	23031,41	11	150,01	23461,02	11	151,7	22940,97	11	150,88	22862,34
12	151,9		12	150,79		12	150,8		12	151,48	
											$f_{m15\times15}$
											38,28
									Standart deviation:		2,35

Table 2 clearly shows that the concrete strength reached 38.28 ± 2.35 MPa, indicating that, overall, the concrete curing results were within the normative range. The cameras were mounted on a tripod at a distance of 2000 mm from the opposite beam surfaces to monitor the condition of the specimens.

Before presenting the data in **Table 3**, it is important to highlight the comparative nature of the conducted experiments. **Table 2** summarizes the results of the initial series of tests, where the compressive strength of concrete cubes was measured under standard curing conditions. These values served as the baseline for further evaluation of the development of the material's mechanical properties.

In contrast, **Table 3** reflects a later stage of testing, where the compressive strength of concrete reached 44.61 MPa. This outcome indicates a progressive enhancement of the internal structure of the material during the curing process and significantly exceeds the results obtained in the previous series. A comparative analysis of **Tables 2** and **3** confirms the positive influence of curing duration on the growth of strength, which is particularly relevant for construction materials science. The higher values recorded in **Table 3** suggest the high reliability of the investigated mix and its potential applicability in structural elements requiring enhanced load-bearing capacity.

Table 3

Concrete Cube Compression Strength Test Conducted on 12.05.2023 (Author's Materials)

12.05.2023											
								Age,14		**28.04.2023**	
Concrete Cube Compressive Strength Test											
1_cube			**2_cube**			**3_cube**			**4_cube**		
Dimension mm		**Mass, gr**	**Dimension mm**		**Mass, gr**	**Dimension mm**		**Mass, gr**	**Dimension mm**		**Mass, gr**
1	155,3	8199	1	152,35	7882	1	152,89	7975	1	151,52	7939
2	155,3	V_c, mm^3	2	150,92	V_c, mm^3	2	151,28	V_c, mm^3	2	151,85	V_c, mm^3
3	154,6	3534656	3	151,69	3462025	3	151,89	3457810	3	152,29	3487037
4	154,3	p, kg/m^3	4	151,26	p, kg/m^3	4	152,51	p, kg/m^3	4	153,44	p, kg/m^3
5	151,2	2319,6	5	152,18	2276,7	5	150,17	2306,4	5	150,46	2276,7
6	151,0	Load, kN	6	151,21	Load, kN	6	150,07	Load, kN	6	150,77	Load, kN
7	150,8	1057,7	7	151,36	1040,2	7	151,50	1023,3	7	150,63	994,8
8	150,5	$R_{15\times15}$, MPa	8	152,08	$R_{15\times15}$, MPa	8	151,53	$R_{15\times15}$, MPa	8	150,90	$R_{15\times15}$, MPa
9	151,6	45,27	9	150,99	45,24	9	150,29	44,60	9	152,11	43,35
10	150,9	A_c, mm^2	10	150,17	A_c, mm^2	10	150,92	A_c, mm^2	10	151,47	A_c, mm^2
11	151,5	23365,76	11	150,91	22992,03	11	150,17	22945,75	11	152,22	22946,32
12	150,9		12	150,23		12	151,40		12	152,06	
											$f_{m15\times15}$
											44,61
									Standart deviation:		0,90

The primary objective today is to optimize the use of collected material data, taking into account the influence of sample shape and testing methods on concrete strength. This need has become the

Many reinforced concrete elements have characteristic differences, with more complex radial cross-sections, which do not correspond to the cross-section of prototype cubes. Therefore, the process of research becomes important in determining the degree to which results obtained from cube testing can be applied to real constructions. It is impossible to cover all the peculiarities of real-world structures within the context of a single study. As a result, the focus of the next section is on the transverse sections of pre-stressed elements, during the operation of which cracks were formed and developed in the compression zone of the cross-section **(Shunzhi Qianab, et al., 2019)**.

When studying the influence of shape, cross-section dimensions, and other factors on strength, as well as possible sources of error, it is reasonable to apply the theory of equilibrium conditions of mechanical systems under the action of applied forces and moments. Consequently, the next examined model demonstrates the collapse of certain concrete elements under compression.

Further below, **Table 4** presents the results of the compressive strength test of a concrete cube carried out on May 19, 2023. The data clearly show that the measured concrete strength reached 47.04 MPa, indicating a notable improvement compared to the previous series of experiments. In addition, the average hardening index was determined to be 1.28, reflecting the progressive development of the material's structural integrity over time.

Table 4
Testing of Concrete Cube for Compressive Strength Conducted on 19.05.2023 (Author's Materials)

19.05.2023											
								Age	**21**		**28.04.2023**
Concrete Cube Compressive Strength Test											
1_cube			**2_cube**			**3_cube**			**4_cube**		
Dimension mm		**Mass, gr**	**Dimension mm**		**Mass, gr**	**Dimension mm**		**Mass, gr**	**Dimension mm**		**Mass, gr**
1	152,33	8056	1	154,30	8238	1	153,12	8030	1	150,86	8002
2	151,14	V_c, mm^3	2	154,08	V_c, mm^3	2	152,44	V_c, mm^3	2	152,73	V_c, mm^3
3	152,18	3452213	3	156,43	3536570	3	151,62	3502244	3	151,36	3472598
4	149,91	p, kg/m^3	4	157,24	p, kg/m^3	4	152,60	p, kg/m^3	4	152,52	p, kg/m^3
5	151,40	2333,6	5	150,46	2329,4	5	150,25	2292,8	5	151,67	2304,3
6	151,08	Load, kN	6	150,40	Load, kN	6	152,52	Load, kN	6	151,23	Load, kN
7	151,89	958,8	7	150,15	1133,4	7	152,36	1071	7	151,25	1063,9
8	151,47	$R_{15\times15}$, MPa	8	149,73	$R_{15\times15}$, MPa	8	151,80	$R_{15\times15}$, MPa	8	151,02	$R_{15\times15}$, MPa
9	150,12	41,82	9	151,42	48,53	9	151,51	46,30	9	151,84	46,30
10	150,80	A_c, mm^2	10	151,49	A_c, mm^2	10	152,30	A_c, mm^2	10	150,58	A_c, mm^2
11	150,25	22929,53	11	151,33	23355,64	11	150,78	23130,86	11	151,51	22976,41
12	151,06		12	151,45		12	151,05		12	150,62	
											$f_{m15\times15}$
											47,04
									Standart deviation:		1,28

Comparing the results shown in **Tables 2** and **3** with those in **Table 4**, we noticed a gradual and stable increase in strength values. This improvement became especially visible after the third week of curing. Most likely, it is connected with better hydration of the cement and denser internal bonding of the mix. Such a tendency was observed for all specimen types, which confirms the reliability of the selected testing method. The tensile stresses acting within a localized zone on a single grain embedded in the natural concrete matrix can initiate minor failures of certain particles within the layer. The breakdown of these fine inclusions subsequently destabilizes the concrete structure and leads to the initiation of surface micro-cracks. It should be noted, however, that the failure of structural volumes within concrete layers does not always represent a negative factor in the overall collapse of the cross-section. Partial damage develops when the cumulative number of failed elements exceeds a critical threshold, which can be regarded as the limit state. The final stage is characterized by the fragmentation of the specimen into several parts. During this ultimate phase, the overall stress in the critical zone approaches the tensile strength of the concrete cross-section, manifested through the propagation of micro-cracks.

Thus, the series of tests on concrete cubes **Tables 1-4** revealed the patterns of strength variation in the material. To validate these findings and broaden the analysis, compressive strength tests were performed on cylindrical specimens, as presented in **Tables 5-6**.

Subsequently, concrete cylinders were tested for compressive strength, as presented in **Table 5** below. The results in **Table 5** clearly indicate that the measured concrete strength reached 41.93 MPa, while the overall hardening index was 0.69. This final experimental stage demonstrated satisfactory outcomes, showing a reliable performance of the material. Moreover, when compared with the results of previous tests presented in **Tables 2-4**, the data from **Table 5** demonstrates a consistent and progressive improvement in the evaluation of the specimens. This indicates the high effectiveness of the applied testing methodology and its reliability in conducting the experiments. The results confirm the validity and reproducibility of the approach used to assess the mechanical properties of the concrete. Furthermore, the observed trends highlight the sensitivity of the testing procedure to variations in specimen behavior, allowing for a detailed analysis of performance differences among cylindrical, cubic, and prismatic samples. These findings provide strong support for the adopted methodology as a reliable tool for experimental concrete research.

Table 5

Compressive strength test of a concrete cylinder conducted in the course of the study (Author's Materials)

Concrete Cylinder Compressive Strength Test														
1_cylinder			2_cylinder			3_cylinder			4_cylinder			5_cylinder		
Dimensin		Mass,	Dimensin		Mass	Dimensin		Mass	Dimensin		Mass	Dimensin		Mass
1	149,5	12025,	1	149,3	12308,0	1	149,1	12049,	1	149,7	12281,0	1	149	1230
2	149,5	V_c, mm^3	2	149,3	V_c, mm^3	2	149,3	V_c, mm^3	2	149,8	V_c, mm^3	2	149	V_c, mm^3
3	149,5	521725	3	149,6	5269849	3	149,2	51984	3	149,9	531246	3	150	5301
4	150,1	p, kg/m^3	4	149,2	p, kg/m^3	4	149,2	p, kg/m^3	4	149,7	p, kg/m^3	4	150	p, kg/m^3
5	296,1	2304,9	5	300,7	2335,6	5	297,2	2317,8	5	301,3	2311,7	5	299	2321,
6	296,5	Load, kN	6	300,7	Load, kN	6	296,8	Load, kN	6	301,1	Load, kN	6	300	Load, kN
7	296,7	729,9	7	300,6	738,9	7	297,0	722,2	7	301,4	754,5	7	299	819,9
8	-	f_{cyl}, MPa	8	-	f_{cyl}, MPa	8	-	f_{cyl}, MPa	8	-	f_{cyl}, MPa	8	-	f_{cyl}, MPa
9	-	41,48	9	-	42,17	9	-	41,27	9	-	42,79	9	-	46,36
10	-	A_c, mm^2	10	-	A_c, mm^2	10	-	A_c, mm^2	10	-	A_c, mm^2	10	-	A_c, mm^2
11	-	17596	11	-	17523,3	11	-	17499	11	-	17632,0	11	-	1768
12	-		12	-		12	-		12	-		12	-	
														41,93
												Standart deviation:		0,69

In **Table 6**, the results of the compressive strength test of a concrete cylinder conducted on 28 April 2023 are presented. The obtained compressive strength was 49.18 Mass, gr, indicating a normal hardening process. This result is higher compared to the value reported in the previous **Table 5**.

Table 6

Concrete Cylinder Compressive Strength Test Conducted on 28.04.2023 (Author's Materials)

Concrete Cylinder Compressive Strength Test														
1_cylinder			2_cylinder			3_cylinder			4_cylinder			5_cylinder		
Dimension		Mass	Dimensin		Mass	Dimensin		Mass	Dimensin		Mass	Dimensin		Mass
1	149,9	12332,	1	149,7	12220	1	149,2	11999,0	1	149,5	12208	1	149,8	12246
2	149,6	V_c, mm^3	2	149,6	V_c, mm^3	2	149,3	V_c, mm^3	2	149,5	V_c, mm^3	2	149,9	V_c, mm^3
3	150,3	531564	3	150,2	52725	3	149,2	5218887	3	149,5	52676	3	149,7	527684
4	150,2	p, kg/m^3	4	150,1	p, kg/m^3	4	150,1	p, kg/m^3	4	149,7	p, kg/m^3	4	149,	p, kg/m^3
5	300,7	2319,9	5	298,6	2317	5	297,4	2299,1	5	299,7	2317	5	298,9	2320,7
6	300,5	Load, kN	6	298,6	Load, kN	6	297,4	Load, kN	6	299,3	Load, kN	6	299,3	Load, kN
7	300,5	914,3	7	298,4	877,3	7	297,3	813,9	7	299,9	827,3	7	299,1	900,7
8	-	f_{cyl}, MPa	8	-	f_{cyl}, MPa	8	-	f_{cyl}, MPa	8	-	f_{cyl}, MPa	8	-	f_{cyl}, MPa
9	-	51,71	9	-	49,68	9	-	46,39	9	-	47,07	9	-	51,04
10	-	A_c, mm^2	10	-	A_c, mm^2	10	-	A_c, mm^2	10	-	A_c, mm^2	10	-	A_c, mm^2
11	-	17682,	11	-	17658	11	-	17546,2	11	-	1757	11	-	17646
12	-		12	-		12	-		12	-		12	-	
														49,18
												Standart deviation		2,37

The tests of cylindrical specimens **Tables 5-6** demonstrated consistent results in terms of compressive strength. Notably, the values obtained in the second series **Table 6** were higher than those in the previous series **Table 5**, indicating a positive trend in concrete hardening. Subsequently, experimental measurements were carried out on three prism specimens under flexural loading, and the results are presented in **Table 7**. The findings showed that the flexural strength of the concrete reached a value of 6.01, demonstrating the material's ability to withstand bending stresses.

Table 7

Flexural strength test of concrete prisms (Author's Materials)

Concrete Prism Flexural Strength Test								
1_prism			**2_prism**			**3_prism**		
Dimensions, mm		**Mass, gr**	**Dimensions, mm**		**Mass, gr**	**Dimensions, mm**		**Mass, gr**
1	101,83	9455	1	101,92	9348	1	100,20	9224
2	101,18	V_c, mm^3	2	100,60	V_c, mm^3	2	101,21	V_c, mm^3
3	102,94	4098783	3	100,20	4036964	3	99,89	4027077
4	100,97	p, kg/m^3	4	101,32	p, kg/m^3	4	101,63	p, kg/m^3
5	100,67	2306,8	5	102,51	2315,6	5	100,24	2290,5
6	100,05	Load, kN	6	97,74	Load, kN	6	100,62	Load, kN
7	100,97	13,55	7	100,94	14,19	7	100,11	13,09
8	101,47	f_{fl}, MPa	8	98,97	f_{fl}, MPa	8	100,44	f_{fl}, MPa
9	400,00	5,90	9	401,00	6,32	9	398,00	5,81
10	401,00	A_c, mm^2	10	402,00	A_c, mm^2	10	399,00	A_c, mm^2
11	399,00	-	11	397,00	-	11	398,00	-
12	399,00		12	398,00		12	398,50	
								6,0
					Standart deviation:			0,27

Metallic collapsible molds were used to prepare the specimens. The concrete mix was compacted using vibrators with a frequency of 2,500 semi-oscillations per minute and an amplitude of 0.45 mm.

As shown in **Table 8**, further experimental measurements were carried out on three additional concrete prisms under flexural loading. The results demonstrated that the flexural strength of the concrete reached 8.36, indicating improved performance compared with the previous series of prism tests.

Table 8

Flexural strength test of concrete prisms (Author's Materials)

Concrete Prism Flexural Strength Test								
4_prism			**5_prism**			**6_prism**		
Dimensions, mm		**Mass, gr**	**Dimensions, mm**		**Mass, gr**	**Dimensions, mm**		**Mass, gr**
1	101,04	9304	1	101,98	9247	1	103,29	9435
2	100,30	V_c, mm^3	2	101,68	V_c, mm^3	2	101,34	V_c, mm^3
3	101,37	4004752	3	100,44	4027835	3	101,62	4177691
4	99,03	p, kg/m^3	4	102,25	p, kg/m^3	4	104,97	p, kg/m^3
5	100,14	2323,2	5	97,29	2295,8	5	101,08	2258,4
6	98,80	Load, kN	6	99,09	Load, kN	6	101,18	Load, kN
7	100,53	19,82	7	96,66	17,68	7	102,58	19,13
8	99,52	f_{fl}, MPa	8	100,01	f_{fl}, MPa	8	103,06	f_{fl}, MPa
9	399,00	8,93	9	404,00	8,11	9	398,00	8,05
10	400,00	A_c, mm^2	10	407,00	A_c, mm^2	10	398,00	A_c, mm^2
11	400,00	-	11	404,00	-	11	400,00	-
12	400,00		12	399,00		12	398,00	
								8,36
						Standart deviation:		0,49

The results showed that the flexural strength of the concrete was 8.36.

Experimental measurements of the following three prisms in bending were carried out on April 28, 2023, the results of which are presented in **Table 8**.

Based on the experimental data from the conducted studies of cast concrete cube specimens, the results of compression tests were compiled into a comprehensive summary table presented in **Table 9**. From this data, a graph illustrating the dependence of the standard deviation of concrete compressive strength over the entire period of experimental measurements was constructed, as shown in **Figure 13.**

Table 9

Overall Experimental Data of Concrete Cube Specimens' Compressive Strength Over the Entire Measurement Period (Author's Materials)

Nr	Mix	Age, days	p, kg/m^3	f_{cyl}, MPa	$f_{c,150x150}$, MPa	Standard deviation
1	Pouring 1	7	2317	30,63	38,28	2,35
		14	2295	35,69	44,61	0,90
		21	2315	37,64	47,04	1,28
		28	2313	41,93	52,41	0,69
		153	2307	49,18	61,47	2,37

The results of compressive strength measurements using the standard destructive testing method for selected specimens exhibited significant scatter, caused both by the heterogeneity of the concrete and other factors (**Sorokina, 2018**).

The variability in compressive strength measurements highlights the inherent heterogeneity of concrete as a composite material. Differences in aggregate distribution, cement paste consistency, and curing conditions can all contribute to the observed scatter in results, even when specimens are prepared under controlled laboratory conditions. Understanding this variability is crucial for interpreting test results and for designing concrete structures with reliable performance.

In addition to statistical evaluation, compressive strength data can be used to assess the quality and uniformity of concrete batches. By analyzing the range of measured values and calculating parameters such as the mean, standard deviation, and coefficient of variation, engineers can ensure that the produced concrete meets the required standards and specifications. This approach allows for informed decisions regarding mix adjustments, quality control, and structural safety.

A key characteristic of concrete is its compressive strength. Until recently, concrete strength was assessed primarily by its grade (denoted by the letter "M" followed by a number indicating the average compressive strength of the specimens in kgf/cm^2).

Currently, the principal strength parameter of concrete defined in regulatory standards is its class, designated by the letter B and a number corresponding to the guaranteed compressive strength in megapascals (MPa). This parameter is determined with a reliability factor of 0.95, which implies that the specified strength is attained in 95% of tested specimens.

Considering the standard deviation of the actual (mean) compressive strength of the concrete specimens, with a 0.95 probability, it can be asserted that the actual (mean) compressive strength of the tested concretes falls within the range:

$$30{,}63\text{MPa} \leq R_B15(M200) \leq 38.28\text{ MPa};$$
$$35{,}69\text{ MPa} \leq R_B15(M200) \leq 44.61\text{ MPa};$$
$$37{,}64\text{ MPa} \leq R_B15(M200) \leq 47.04\text{ MPa};$$
$$41{,}93\text{ MPa} \leq R_B15(M200) \leq 52.41\text{ MPa};$$
$$49{,}18\text{ MPa} \leq R_B15(M200) \leq 61.47\text{ MPa};$$

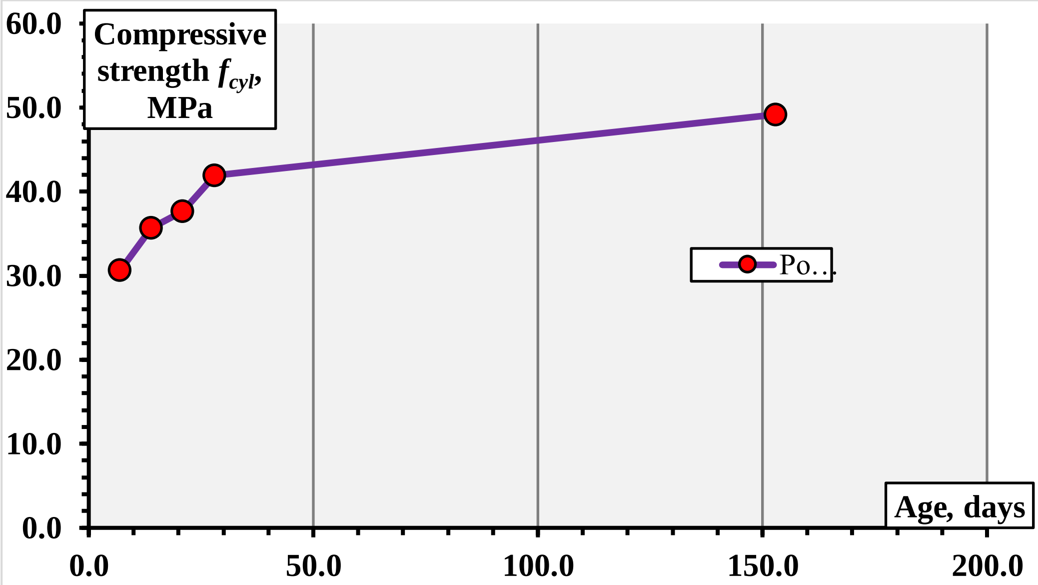

Figure 13 – Standard Deviation of Concrete Compressive Strength (Author's Materials)

The essence of the influence of the water–cement ratio on concrete strength is as follows. The amount of water added to the concrete mix always exceeds the amount required for chemical interaction with cement. This is necessary to provide the mixture with sufficient workability for dense placement. As the excess water evaporates, pores form within the concrete, which leads to a reduction in concrete density, the effective cross-sectional area of the structure, and, consequently, a decrease in strength. **Figure 13** graphically illustrates the total elapsed time after casting the concrete cubes and the effect of the water–cement ratio on compressive strength.

5 CONCLUSIONS

1. Based on the results obtained, it can be noted that non-destructive testing methods are convenient when quick evaluation is required, for example, at construction sites. Nevertheless, destructive testing remains the most accurate way to study the actual mechanical behavior of concrete under load. The experiments confirmed that the volume of the element has little influence on strength, while the increase of surface area tends to reduce it. In practice, this means that the choice of testing method should depend on the research goal and available equipment.
2. The studies demonstrated a practical absence of influence of the element's volume on its compressive strength and, consequently, on microfracture processes.
3. At the same time, increasing the surface area of an element while keeping its volume constant results in a decrease in concrete strength and a reduction in the extent of micro-crack formation. This finding is confirmed by the experimental results obtained from specimens with channels that substantially enlarge the element's surface area.
4. Based on the obtained experimental results, the coefficient of variation of the strength parameters of the specimens presented in the tables and in the diagram was determined. The specimens were produced using three different methods, with a minimum of 10 samples for each type.
5. High coefficients of variation were obtained because the experiments were performed on small-scale specimens (cubes, cylinders, and prisms). Sampling of such small elements from the concrete body results in significant variability of properties, consistent with the heterogeneous nature of concrete.
6. Using averaged properties for stress assessment can lead to significant errors in determining actual stresses. Therefore, it is necessary to determine individual characteristics for each point of the study.

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RESEARCH ARTICLE

ON THE SEISMIC RESISTANCE OF BRICK BUILDINGS BASED ON EXPANDED CLAY WITH COAL MINING WASTE AND INORGANIC ADDITIVES

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Abstract. *Lightweight double-layer concrete walls with a 6-8 cm thick structural concrete layer are effective in earthquake-resistant construction. The development of lightweight concrete production is particularly important for Southern Kazakhstan due to its high seismicity. Reducing the weight of individual structures, as well as buildings and structures as a whole, through the use of lightweight expanded clay concrete can be considered as a measure to improve their seismic resistance. The study examines the effect of inorganic additives and coal mining waste as swelling intensifiers in expanded clay production to improve the seismic resistance of brick buildings. The material composition of the clays studied, as well as the mineralogical and structural properties of the constituent mineral phases, were studied using electron microscopy. Experimental firings of Kyngrak-Keles bentonite clay samples were conducted with the addition of the following mineral salts and non-ferrous metallurgy waste: sodium chloride, calcium chloride, polymetallic ore beneficiation waste, and coal mining waste. It was found that with the addition of 0.5% NaCl and a firing temperature of 1180°C, the resulting expanded clay has a bulk density of 0.89 g/cm^3, which corresponds to a bulk density of 580 kg/m^3. With the addition of 0.5% $CaCl_2$, the bulk density at the same temperature is 0.99 g/cm^3 (bulk density is 650 kg/m^3).*

Keywords: *seismic resistance of brick buildings, inorganic additives, coal mining waste, swelling intensifiers, expanded clay.*

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КӨМІР ӨНДІРУ ҚАЛДЫҚТАРЫ МЕН БЕЙОРГАНИКАЛЫҚ ҚОСПАЛАРЫ БАР КЕРАМЗИТ НЕГІЗІНДЕГІ КІРПІШ ҒИМАРАТТАРДЫҢ СЕЙСМИКАЛЫҚ ТӨЗІМДІЛІГІ ТУРАЛЫ

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Аңдатпа. *Жер сілкінісіне төзімді құрылыста 6-8 см қалың құрылымдық бетон қабаты бар жеңіл екі қабатты бетон қабырғалары тиімді. Жеңіл бетон өндірісін дамыту Оңтүстік Қазақстан үшін сейсмикалық жоғары болғандықтан ерекше маңызды. Жеңіл керамзит бетонды қолдану арқылы жекелеген құрылымдардың, сондай-ақ жалпы ғимараттар мен құрылыстардың салмағын азайту олардың сейсмикалық төзімділігін арттыру шарасы ретінде қарастырылуы мүмкін. Зерттеулер кірпіш ғимараттардың жер сілкінісіне төзімділігін арттыру үшін керамзит өндірісіндегі бейорганикалық қоспалар мен көмір өндіретін қалдықтардың әсерін зерттеуге арналған. Зерттелетін саздардың заттық құрамы, минералды фазалардың құрамдас бөліктерінің минералогиялық және құрылымдық ерекшеліктері электронды-микроскопиялық талдау арқылы зерттелді. Келесі минералды тұздар мен түсті металлургия қалдықтары: натрий хлориді, кальций хлориді, полиметалл кендерін байыту қалдықтары, сондай-ақ көмір өндіру қалдықтары қосылған Қыңғрақ-Келес бентонит саздарының үлгілерін эксперименттік күйдіру жүргізілді. 0,5% NaCl және 1180^{0}С күйдіру температурасын енгізген кезде алынған кеңейтілген саздың түйіршіктегі көлемдік массасы 0,89 г/см^3 болатыны анықталды, бұл кеңейтілген саздың 580 кг/м^3 көлемдік массасына сәйкес келеді. 0,5% $CaCl_2$ қоспасымен бірдей температурадағы көлемдік масса 0,99 г/см^3 (жаппай масса 650 кг/м^3).*

Түйін сөздер: *кірпіш ғимараттардың сейсмикалық төзімділігі, бейорганикалық қоспалар, көмір өндіру қалдықтары, ісіну күшейткіштер, керамзит.*

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НАУЧНАЯ СТАТЬЯ

О СЕЙСМОСТОЙКОСТИ КИРПИЧНЫХ ЗДАНИЙ НА ОСНОВЕ КЕРАМЗИТА С ОТХОДАМИ УГЛЕДОБЫЧИ И НЕОРГАНИЧЕСКИХ ДОБАВОК

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Аннотация. *Легкобетонные двухслойные стены со слоем конструктивного бетона толщиной 6-8 см эффективны в условиях сейсмостойкого строительства. Особое значение для Южного Казахстана приобретает развитие производства легких бетонов в связи с высокой их сейсмичностью. 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. Исследования посвящены изучению влияния неорганических добавок и отходов угледобычи как интенсификаторов вспучивания в производстве керамзита для повышения сейсмостойкости кирпичных зданий. Вещественный состав исследуемых глин, минералогические и структурные особенности составляющих минеральных фаз был изучен с помощью электронно-микроскопического анализа. Были проведены экспериментальные обжиги образцов из кынграк-келесских бентонитовых глин с добавкой следующих минеральных солей и отходов цветной металлургии: хлористого натрия, хлористого кальция, отходы обогащения полиметаллических руд, а также отходов угледобычи. Установлено, что при введении 0,5% NaCl и температуре обжига 1180^{0}С полученный керамзит имеет объемную массу в грануле 0,89 г/см^3, что соответствует насыпной массе керамзита, равной 580 кг/м^3. При добавке 0,5% $CaCl_2$ объемная масса при той же температуре равна 0,99 г/см^3 (насыпная масса равна 650 кг/м^3).*

Ключевые слова: *сейсмостойкость кирпичных зданий, неорганические добавки, отходы угледобычи, интенсификаторы вспучивания, керамзит.*

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CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

The authors declare that no generative artificial intelligence technologies or AI-based tools were used in the preparation of this article.

АЛҒЫС / ҚАРЖЫЛАНДЫРУ КӨЗІ

Зерттеу жеке қаржыландыру көздерін пайдалана отырып жүргізілді.

МҮДДЕЛЕР ҚАҚТЫҒЫСЫ

Авторлар мүдделер қақтығысы жоқ деп мәлімдейді.

Авторлар мақаланы дайындау барысында генеративті жасанды интеллект технологиялары мен жасанды интеллектке негізделген технологияларды пайдаланбағанын мәлімдейді.

БЛАГОДАРНОСТИ/ИСТОЧНИК ФИНАНСИРОВАНИЯ

Исследование проводилось с использованием частных источников финансирования.

КОНФЛИКТ ИНТЕРЕСОВ

Авторы заявляют, что конфликта интересов нет.

Авторы заявляют о том, что при подготовке статьи не использовались технологии генеративного искусственного интеллекта и технологии, основанные на искусственном интеллекте.

1 INTRODUCTION

Massive housing construction in large cities with unfavorable engineering and geological conditions and extremely limited expansion potential places high demands on the reliability and cost-effectiveness of multi-story buildings and structures constructed in high-seismic zones. In recent decades, earthquake engineering specialists have been working to develop and apply new methods for seismic insulation of brick buildings and structures. In today's construction environment, reducing the weight of building structures through the use of lightweight concrete and ceramic materials, including expanded clay, is particularly important. This will contribute to improving the seismic resistance of brick buildings **(Hafner et al., 2023)**.

For most artificial aggregates, obtaining granules with the required density depends on the amount of gaseous products released or introduced and retained in the pyroplastic mass. One such gaseous product, iron and calcium oxides, can be one example. Iron oxide (Fe_2O_3), converted to a ferrous state as a result of reduction processes, reacts vigorously with aluminum and silicon oxides, forming a series of eutectics and solutions of complex composition and exerting a strong fluxing effect. One such compound of iron oxide (FeO) with silica is fayalite, which melts at 1205°C, i.e., within the temperature range for producing expanded clay. Also possessing high wetting capacity, FeO promotes the formation of a system with optimal softening parameters, enabling intense and complete swelling. Clays containing iron in the form of oxides and hydroxides exhibit good swelling properties. Calcium oxide shortens the swelling range of the rock, and at high concentrations, by sharply reducing the viscosity of the liquid phase over a short temperature range, it causes rapid deformation and adhesion of the material, complicating firing. Alkali and alkaline earth oxides also participate in the formation of eutectic melts, with their fluxing effect decreasing in the order Na_2O, K_2O, FeO, CaO, and MgO. Clay minerals such as montmorillonite, mica, and hydromica can also be sources of gas formation **(Zhakipbayev et al., 2021)**.

The following features of the production of artificial porous fillers can be noted:

- raw material porosity during heat treatment is caused by the release of gaseous products into the raw material during firing;
- swelling processes occur in the pyroplastic state of the material, therefore, the viscosity of the liquid phase has the primary influence on swelling;
- high-speed firing of the raw material promotes a shift in gas formation processes to higher temperatures, and the coincidence of these processes with the transition of some of the raw material from a eutectic or near-eutectic composition to a pyroplastic state, which facilitates intense swelling;
- the transition of some of the raw material to a pyroplastic state usually occurs at temperatures no higher than 1250°C.

Clays suitable for expanded clay production should not exceed 30% dust content, should not contain carbonates with a grain size greater than 0.2 mm, and should not contain more than 1-2% organic inclusions. However, the limited availability of such raw materials and the need to ensure the cost-effectiveness of the process raise the question of using additives and industrial waste whose chemical composition meets the requirements for expanded clay raw materials. It is known that inorganic substances containing alkaline and alkaline earth element compounds promote the formation of a liquid phase at low temperatures. Therefore, the addition of mineralizers to the batch can reduce the temperature at which the mass transitions to a pyroplastic state or the firing temperature of expanded clay. In order to reduce the firing temperature and intensify swelling, experimental firings of samples of Kyngrak-Keles bentonite clays were carried out with the addition of the following mineral salts and non-ferrous metallurgy waste: sodium chloride, calcium chloride, polymetallic ore beneficiation waste, and coal mining waste **(Seiitkassymuly et al., 2025)**.

2 LITERATURE REVIEW

A study **(Gulfem et al., 2022; Vandanapu et al., 2018)** assessed the feasibility of using coal mining waste as a raw material for brick production. Dry-crushed waste was added to clay in proportions ranging from 0 to 100%, and the samples were fired at temperatures up to 1150°C. All resulting bricks met Turkish strength standards, confirming the suitability of the waste as an alternative building material and offering an environmentally friendly solution to its disposal.

The authors' study **(Xiaogang et al., 2025; Kalman Šipoš et al., 2019)** proposes a method for assessing the seismic resistance of buildings damaged by mining activities based on energy dissipation theory. It was found that ground subsidence reduces the rigidity of buildings, lengthens their natural period, and amplifies torsional vibrations under seismic loads. Numerical modeling showed an increase in displacements and internal forces, especially on the lower floors. As a solution, they propose a protection system combining underground backfill and surface isolation, providing practical guidance for seismic design in mining areas.

The authors **(Soumitra et al., 2024; Khan et al., 2023)** explore a new approach to the design of clay brick structures based on extensive shear testing, developing numerical models and failure criteria, which improves the accuracy of calculations and the reliability of buildings such under seismic loading. Modern brick buildings must not only meet architectural and functional requirements but also be effectively designed for structural stability, energy efficiency, and seismic resistance. However, the complex combination of these requirements makes testing their behavior under seismic loads challenging.

A research **(Mohammad Ali Esmaili-Tafti et al., 2025; Chourasia et al., 2020)** first analyzed the seismic performance of cold-formed steel frame (CFSF) shear walls constructed using different installation methods and stud spacings. Six walls, varying in size, brick placement order, and the presence of insulation, were fabricated and tested. The results showed that simultaneous wall construction and increased stud spacing increased shear strength but had little effect on seismic performance. The Wang and Pauli methods also yielded similar design parameters.

A study **(Shoaib Ur Rehman et al., 2025; Agrawal et al., 2021)** examines the use of confined masonry structures (CBMS) to improve the seismic performance of residential buildings. A comparative numerical analysis of CBMS, traditional masonry structures (CMS), and framed structures (FS) revealed that CBMS exhibit the lowest deformations and displacements under seismic loading. Due to their concrete infill, such walls exhibit increased ductility and stability, offering an effective solution for mitigating seismic damage.

A research work **(As'at Pujianto et al., 2024; Bagnoli et al., 2021)** examined the technical properties of lightweight concrete with expanded clay aggregate for improving the seismic resistance of infrastructure. Experiments showed that the oval aggregate shape provides superior strength and density characteristics, while the optimal amount of superplasticizer (up to 2.5%) improves the properties of both fresh and hardened concrete. The results confirm the potential of expanded clay as an environmentally friendly and effective material for lightweight seismic-resistant structures.

3 MATERIALS AND METHODS

The Turkestan region is one of the richest in expanded clay raw materials with the location of large and very promising for the development of such deposits of bentonite and bentonite-like clays as Kyngrak-Keles. These clays consist mainly of minerals of the montmorillonite group $Al_2[Si_4O_{10}](OH)_2*nH_2O$ and are capable of swelling during firing. The chemical composition of the Kyngrak-Keles bentonite clays is represented by the composition (%): SiO_2 - 63.0; Al_2O_3 - 13.0; Fe_2O_3 - 5.40; CaO - 4.48; MgO - 3.35; K_2O - 2.0; Na_2O - 1.45; TiO_2 - 0.95; FeO - 0.85; SO_3 - 5.55.

For a more in-depth study of the material composition of the clays under study, the mineralogical and structural features of the constituent mineral phases, electron microscopic analysis was used on a scanning electron microscope SEM JSM-6490LV, where we recorded the following elements: Si; O; Fe; K; Mg; Ca **(Figure 1)**.

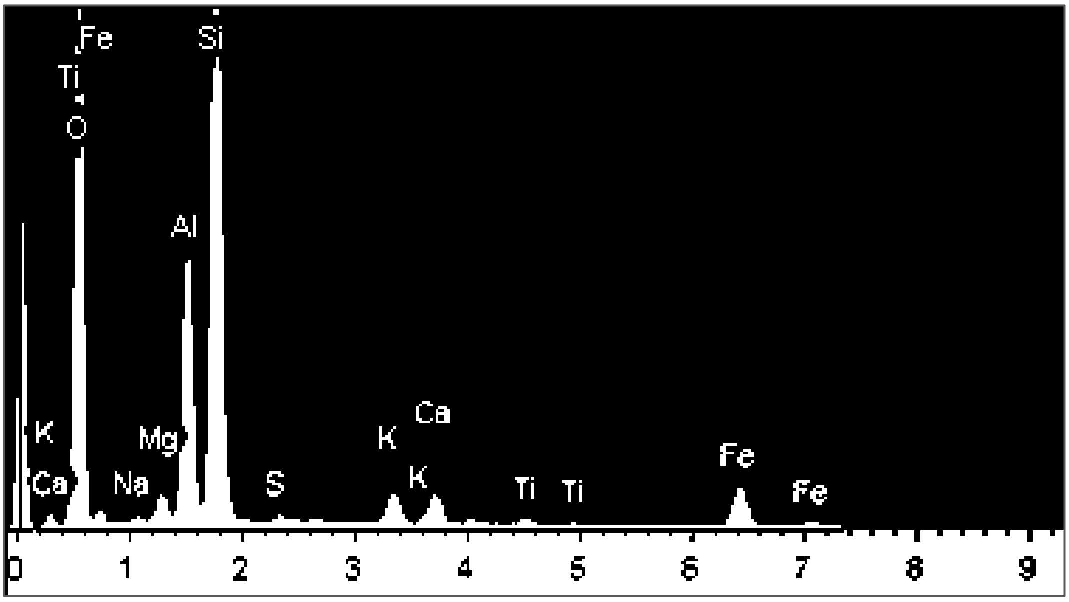

Figure 1 – Energy-dispersive SEM spectrum of Kyngrak-Keles bentonite clays

Figure 1 shows the characteristic presence of iron oxide in the studied clays. Iron oxide, converted to a ferrous state as a result of reduction processes, actively reacts with aluminum and silicon oxides, forming a series of eutectics and solutions of complex composition, while exerting a strong fluxing effect. Also possessing greater wetting capacity, FeO promotes the formation of a system with optimal softening parameters, which facilitates intensive and complete swelling.

4 RESULTS AND DISCUSSION

The results of tests of expanded clay obtained from Kyngrak-Keles bentonite clays with the introduction of mineral additives are shown in **Table 1** and **Figures 2 and 3**.

Table 1
Physical and mechanical properties of expanded clays based on Kyngrak-Keles bentonite clays with the introduction of inorganic additives

Burning temperature, ^{0}C	Swelling coefficient		
	0,5% $CaCl_2$	0,5% NaCl	7% of polymetallic ore beneficiation waste
1080	1,02	0,82	1,22
1100	0,95	0,91	1,37
1120	1,03	0,98	1,38
1140	1,30	1,05	1,49
1160	1,33	1,22	1,61
1180	1,52	1,58	1,65
Burning temperature, ^{0}C	**Bulk density, g/cm^3**		
1080	1,48	1,69	1,35
1100	1,52	1,52	1,20
1120	1,44	1,43	1,18
1140	1,18	1,32	1,07
1160	1,15	1,14	0,98
1180	0,98	0,90	0,92

The presented results show that with the addition of 0.5% NaCl and a firing temperature of 1180^{0}C, the resulting expanded clay has a bulk density in granules of 0.89 g/cm^3, which corresponds to a bulk density of expanded clay equal to 580 kg/m^3. With the addition of 0.5% $CaCl_2$, the bulk density at the same temperature is equal to 0.99 g/cm^3 (bulk density is equal to 650 kg/m^3).

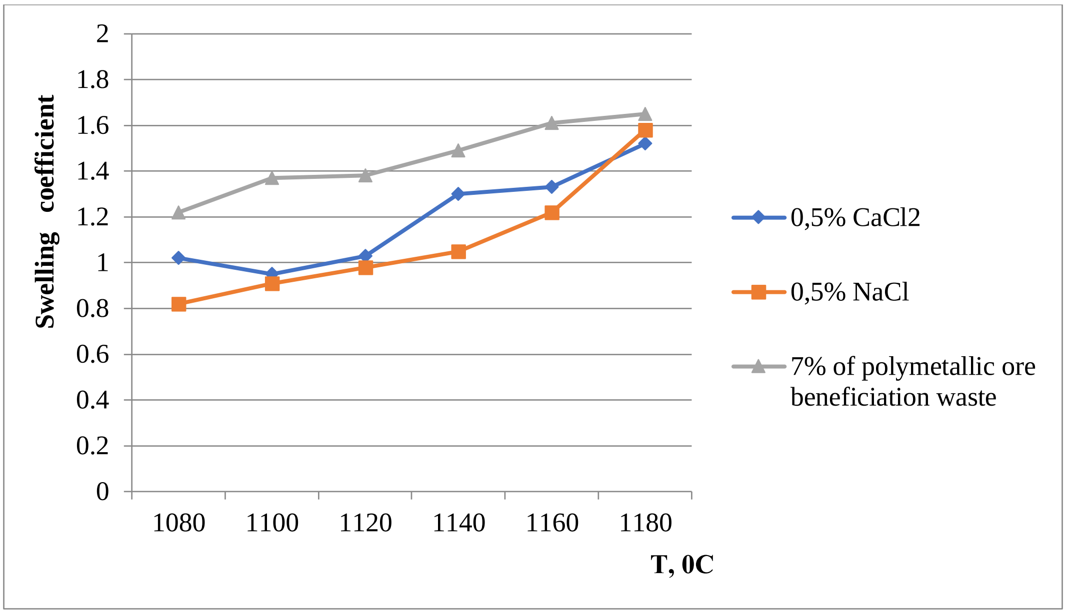

Figure 2 – Change in the swelling coefficient of the obtained expanded clay based on Kyngrak-Keles bentonite clays with the introduction of inorganic additives depending on the firing temperature

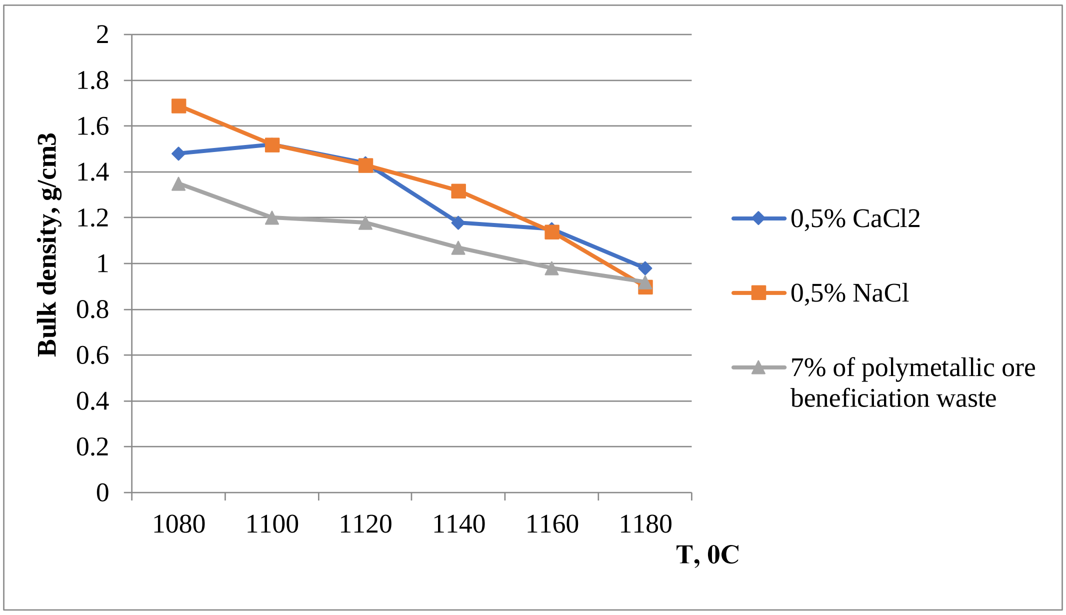

Figure 3 – Change in the bulk density of the obtained expanded clay based on Kyngrak-Keles bentonite clays with the introduction of inorganic additives depending on the firing temperature

When 7% of polymetallic ore beneficiation waste was added, the performance of the resulting expanded clay was inferior to that of expanded clay from pure clay.

Seven masses of coal mining waste were tested in the range of 1-10% additive added. The results presented in **Table 2** and **Figures 4 and 5** indicate that coal mining waste cannot serve as an expanding additive for kyngrak-keles bentonite clays.

Table 2

Physical and mechanical properties of expanded clays based on kyngrak-keles bentonite clays with the addition of coal mining waste

Burning temperature, ^{0}C	% coal mining waste					
	1	3	5	7	10	
1080	0,7	1,0	0,9	0,9	1,0	**Swelling coefficient**
1100	0,9	1,1	1,0	1,1	1,1	
1120	1,1	1,2	1,1	1,2	1,2	
1140	1,3	1,3	1,2	1,3	1,3	
1160	1,6	1,4	1,3	1,4	1,4	
1180	1,7	1,8	1,4	1,5	1,5	
1200	1,8	2,0	1,5	1,6	1,6	
Burning temperature, ^{0}C	**% coal mining waste**					
	1	3	5	7	10	
1080	1,80	1,55	1,60	1,66	1,38	**Bulk density, g/cm^3**
1100	1,69	1,53	1,38	1,32	1,26	
1120	1,56	1,44	1,20	1,16	1,12	
1140	1,32	1,18	1,17	1,04	1,16	
1160	1,12	0,99	0,98	1,03	0,98	
1180	1,05	0,82	0,95	0,86	0,95	
1200	0,98	0,76	0,94	0,85	0,86	

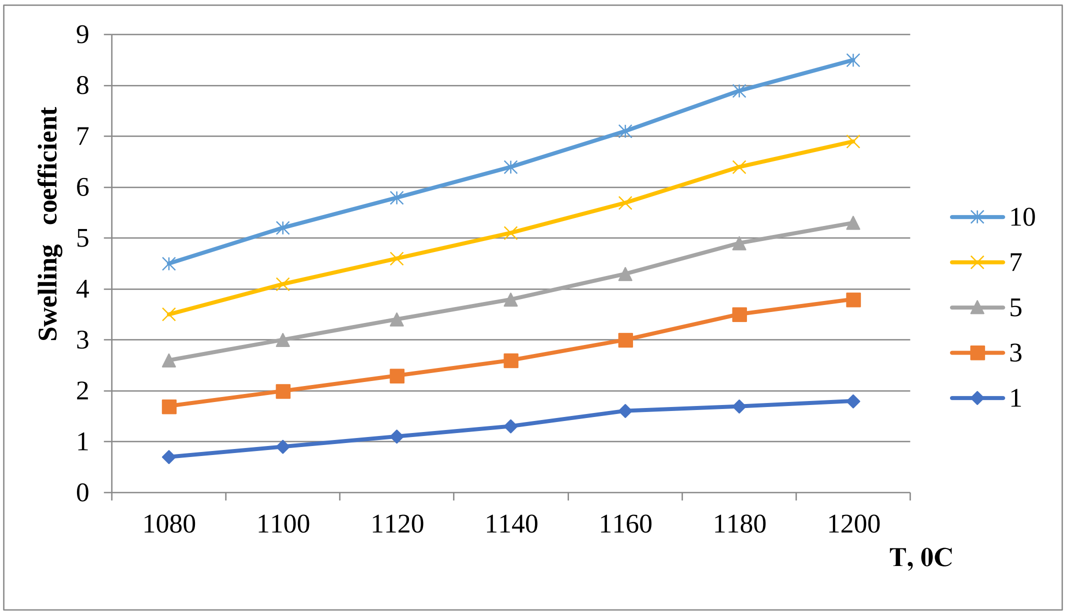

Figure 4 – Change in the swelling coefficient of the obtained expanded clay based on Kyngrak-Keles bentonite clays with the addition of coal mining waste depending on the firing temperature

The addition of 1-10% coal mining waste had virtually no effect on clay expansion. The expansion coefficient was lower, and the bulk density of the granules was virtually identical to those of expanded clay from kyngrak-keles bentonite clays without additives. Only the addition of 7% and 10% coal mining waste slightly decreased the bulk density. Apparently, this additive acts as a leaning agent for the studied clay, but does not promote expansion. The ash residue of the coal mining waste reaches 65-75% of the total mass and, being refractory in nature, shifts the onset of liquid phase formation to higher temperatures. Therefore, at the temperatures accepted for expanded clay firing, the granules do not have time to transform into a pyroplastic state and expand very weakly.

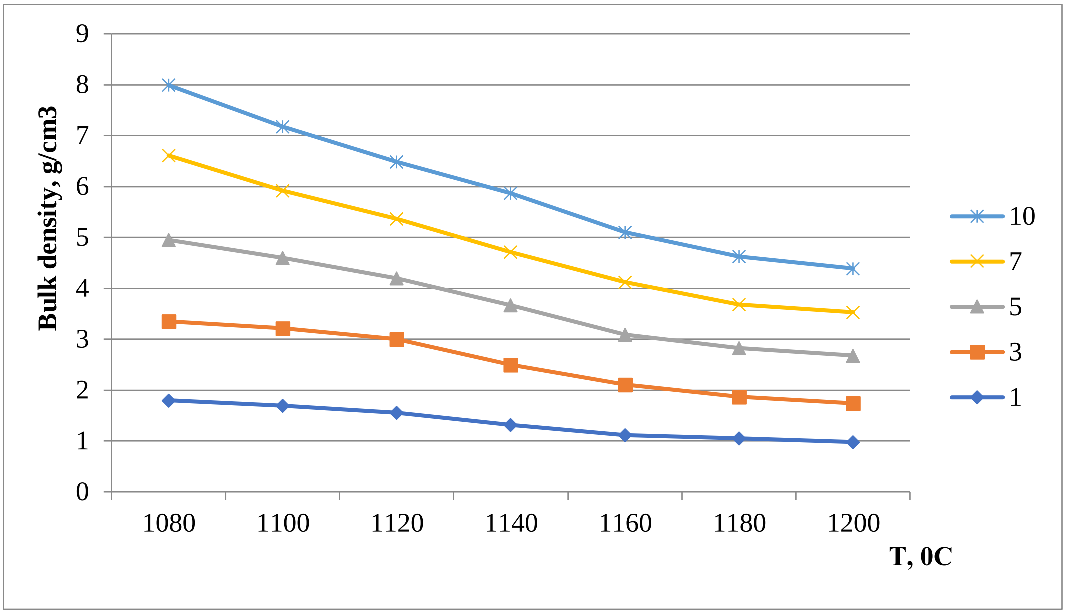

Figure 5 – Change in the bulk density of the obtained expanded clay based on Kyngrak-Keles bentonite clays with the addition of coal mining waste depending on the firing temperature

5 CONCLUSIONS

1. It was found that with the addition of 0.5% NaCl and a firing temperature of 1180^{0}C, the resulting expanded clay has a bulk density of 0.89 g/cm^3 per granule, which corresponds to a bulk density of 580 kg/m^3. With the addition of 0.5% $CaCl_2$, the bulk density at the same temperature is 0.99 g/cm^3 (bulk density is 650 kg/m^3).
2. It was found that the swelling coefficient is lower, and the bulk density of the granules is almost the same as these indicators of expanded clay from Kyngrak-Keles bentonite clays without additives.
3. 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 other finely dispersed components in the melt, 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.
4. During heat treatment, 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.

Thus, it has been established that for obtaining expanded clay, inorganic additives can only be used in combination with organic ones.

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RESEARCH ARTICLE

OPTIMIZATION OF ASPHALT CONCRETE PROPERTIES THROUGH MODELING

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Abstract. *This study presents the results of mathematical modeling of the thermal conductivity and strength properties of asphalt concrete mixtures, utilizing a three-factor Box–Behnken experimental design implemented within the STATISTICA software environment. The variable factors considered in the modeling were the temperature of technological processing, the duration of thermal exposure, and the gravel-to-bitumen content ratio in the mixture. The main objective was to quantitatively evaluate the impact of composition and thermal strengthening conditions on the thermal and mechanical performance of asphalt concrete. These performance indicators are highly important for the effective design, construction, and long-term operation of road structures in diverse climatic regions. To determine the statistical significance of the studied factors, analysis of variance (ANOVA) was conducted. Regression equations for the response functions were developed, and response surface plots as well as main effects profiles were generated. The results demonstrated that the bitumen content and processing temperature significantly influenced the strength characteristics, whereas thermal conductivity exhibited lower sensitivity to parameter variations. High values of determination coefficients (R^2 and adjusted R^2) confirmed the consistency between the statistical models and experimental outcomes. In addition, engineering calculations addressing pavement freezing depth and design soil moisture were performed using the modeled thermal properties of asphalt concrete. These findings confirmed the practical applicability of the developed model, showing that optimization of mixture composition contributes to improved pavement durability, enhanced energy efficiency, and the development of updated regulatory standards and advanced road construction technologies.*

Keywords: *asphalt concrete, thermal conductivity, mechanical strength, moisture content, STATISTICA, ANOVA, Box–Behnken design, regression modeling, freezing depth, thermal strengthening.*

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АСФАЛЬТОБЕТОН ҚАСИЕТТЕРІН МОДЕЛЬДЕУ АРҚЫЛЫ ОҢТАЙЛАНДЫРУ

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Аңдатпа. *Бұл зерттеуде STATISTICA бағдарламалық ортасында жүзеге асырылған үш факторлы Box–Behnken тәжірибелік жоспары қолданылып, асфальтобетон қоспаларының жылуөткізгіштігі мен беріктік қасиеттеріне бағытталған математикалық модельдеу нәтижелері ұсынылды. Модельдеуде қарастырылған негізгі айнымалы факторлар – технологиялық өңдеу температурасы, термиялық әсер ету ұзақтығы және қиыршық тас пен битумның қоспадағы арақатынасы болды. Зерттеудің басты мақсаты – асфальтобетонның жылу-техникалық және механикалық көрсеткіштеріне құрам мен термиялық қатайту жағдайларының әсерін сандық тұрғыдан бағалау. Бұл көрсеткіштер әртүрлі климаттық жағдайларда жол құрылымдарын тиімді жобалау, салу және ұзақ мерзімді пайдалану үшін ерекше маңызға ие. Факторлардың статистикалық маңыздылығын анықтау мақсатында дисперсиялық талдау (ANOVA) жүргізілді. Жауап функциялары үшін регрессиялық теңдеулер құрылып, жауап беттерінің графиктері мен негізгі әсерлердің профильдері жасалды. Нәтижелер битум мөлшері мен өңдеу температурасының беріктік сипаттамаларына айтарлықтай ықпал ететінін, ал жылуөткізгіштіктің параметрлердің өзгерісіне төменірек сезімталдық танытатынын көрсетті. Детерминация коэффициенттерінің (R^2 және түзетілген R^2) жоғары мәндері статистикалық модельдер мен тәжірибелік деректер арасындағы сәйкестікті растады. Сонымен қатар, асфальтобетонның жылутехникалық қасиеттеріне сүйене отырып, жол жабындарының тоңу тереңдігі мен топырақтың есептік ылғалдылығына байланысты инженерлік есептер орындалды. Бұл нәтижелер ұсынылған модельдің практикалық құндылығын дәлелдеп, қоспа құрамын оңтайландыру арқылы жол жабындарының беріктігін арттыруға, энергия тиімділігін жоғарылатуға және нормативтік құжаттарды жетілдіруге мүмкіндік беретінін көрсетті.*

Түйін сөздер: *асфальтобетон, жылуөткізгіштік, беріктік, ылғалдылық, STATISTICA, ANOVA, Box–Behnken жоспары, регрессиялық модельдеу, тоңу тереңдігі, термиялық қатайту.*

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НАУЧНАЯ СТАТЬЯ

ОПТИМИЗАЦИЯ СВОЙСТВ АСФАЛЬТОБЕТОНА С ПОМОЩЬЮ МОДЕЛИРОВАНИЯ

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Аннотация. *В статье представлены результаты математического моделирования теплопроводности и прочности асфальтобетонных смесей с применением трёхфакторного планирования эксперимента Бокса–Бенкена, выполненного в программной среде STATISTICA. В качестве варьируемых факторов рассматривались температура технологической обработки, продолжительность термического воздействия и соотношение щебня и битума в составе смеси. Основной целью исследования являлась количественная оценка влияния состава и условий термоупрочнения на теплотехнические и прочностные характеристики асфальтобетона. Эти показатели имеют особое значение при проектировании, строительстве и эксплуатации дорожных конструкций в различных климатических условиях. Для оценки статистической значимости факторов был проведён дисперсионный анализ (ANOVA). Построены регрессионные уравнения отклика, поверхности отклика и профили основных эффектов. Результаты показали, что содержание битума и температура обработки оказывают наиболее сильное влияние на прочностные характеристики, тогда как теплопроводность в меньшей степени зависит от варьируемых параметров. Высокие значения коэффициентов детерминации (R^2 и скорректированного R^2) подтвердили достоверность статистических моделей и их согласованность с экспериментальными данными. Дополнительно были выполнены инженерные расчёты глубины промерзания и расчётной влажности грунта дорожных одежд с использованием полученных теплотехнических свойств асфальтобетона. Эти результаты подтвердили практическую применимость разработанной модели, показав, что оптимизация состава позволяет повысить долговечность дорожных покрытий, улучшить их энергоэффективность, а также использовать данные выводы при разработке нормативной документации и совершенствовании технологий дорожного строительства.*

Ключевые слова:. *асфальтобетон, теплопроводность, прочность, влажность, STATISTICA, ANOVA, трёхфакторный эксперимент, план Бокса–Бенкена, глубина промерзания, термоупрочнение.*

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CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

During the preparation of this manuscript, the authors used artificial intelligence tools (ChatGPT) solely for editorial assistance, such as improving phrasing and checking grammar, spelling, and punctuation. All ideas, interpretations, and conclusions are the responsibility of the authors, who take full accountability for the content of the article.

АЛҒЫС / ҚАРЖЫЛАНДЫРУ КӨЗІ

Зерттеу жеке қаржыландыру көздерін пайдалана отырып жүргізілді.

МҮДДЕЛЕР ҚАҚТЫҒЫСЫ

Авторлар мүдделер қақтығысы жоқ деп мәлімдейді.

Мақаланы дайындау барысында авторлар жасанды интеллект құралдарын (ChatGPT) тек редакциялық көмек мақсатында пайдаланды: тұжырымдарды жетілдіру, грамматикалық, орфографиялық және тыныс белгілеріндегі қателерді тексеру үшін. Барлық идеялар, интерпретациялар мен қорытындылар авторларға тиесілі, және олар мақаланың мазмұнына толық жауапты.

БЛАГОДАРНОСТИ/ИСТОЧНИК ФИНАНСИРОВАНИЯ

Исследование проводилось с использованием частных источников финансирования.

КОНФЛИКТ ИНТЕРЕСОВ

Авторы заявляют, что конфликта интересов нет.

При подготовке рукописи авторы использовали инструменты искусственного интеллекта (ChatGPT) исключительно для редакторской поддержки: корректировки формулировок, проверки грамматических, орфографических и пунктуационных ошибок. Все идеи, интерпретации и выводы принадлежат авторам, которые несут полную ответственность за содержание статьи.

1 INTRODUCTION

Modern requirements for the quality of the road surface necessitate a comprehensive assessment of its thermal and strength characteristics. This is especially important when designing coatings in conditions of contrasting temperatures and seasonal climate fluctuations. Asphalt concrete mixtures are multicomponent systems, the properties of which depend on the composition, preparation technology and operating conditions. The most significant factors affecting the thermal conductivity and strength of asphalt concrete are the content of crushed stone, the content of bitumen, as well as the pore structure and the degree of saturation with water in the material.

The purpose of this work is to construct statistical models (empirical equations) of thermal conductivity and strength of asphalt concrete mortar based on the experimental three-factor Box-Behnken plan; to conduct a dispersion analysis of the significance of the factors; to study the effect of the moisture state of the material on thermal conductivity; and to apply the simulation results to assess the depth of freezing and the calculated moisture content of the substrate. The realization of this goal will make it possible to develop recommendations for optimizing the composition and technology of preparing asphalt mixtures with specified characteristics.

2 LITERATURE REVIEW

The literature emphasizes that the physical and mechanical properties of pavement materials significantly affect its durability. In particular, the thermal properties of the upper layers of the road play a role in resistance to climatic influences**.** (**Kravchenko & Reut, 2020**). Thus, it is necessary to take into account the thermophysical characteristics of the pavement layers when designing it in order to prevent excessive freezing and related damage. High temperatures in summer and extremely low temperatures in winter create a tense thermal regime of the structure, which can lead to cracks and deterioration of the bearing capacity of the roadbed. At the same time, the strength characteristics of asphalt concrete, for example, resistance to track formation and fatigue strength, determine the ability of the coating to withstand transport loads without destruction.. (**Fredlund & Rahardjo, 2018**).

Special attention has recently been paid to the effect of moisture and water saturation on the properties of asphalt concrete and base soils. Under humidification conditions, the thermal conductivity of materials usually increases, since water has a higher coefficient of thermal conductivity (~0.58 W/m·K) than air (~0.024 W/m·K), which fills the pores in a dry state. (**Brown & Davis, 2020**). Studies show that when the pores of asphalt concrete are saturated with water, its effective thermal conductivity can increase by 20-30% compared to the dry state. On the other hand, moisture negatively affects the strength and durability of asphalt concrete: bitumen loses its adhesion to crushed stone (the "softening" effect), and compressive strength and fatigue resistance decrease. Freeze-thaw cycles are especially harmful, which, in the presence of moisture in the pores, lead to cracks and accelerated destruction of the coating. (**San et al., 2022**). Thus, for regions with heavy precipitation or high groundwater levels, it is important to evaluate the properties of asphalt concrete in both dry and wet conditions. In arid regions, on the contrary, insufficient soil moisture may become a problem, affecting the quality of compaction and requiring special calculation methods. (**Kiyalbaev et al., 2018**).

Previously, studies have been conducted that emphasize the importance of integrated consideration of thermal and strength properties in the design of road clothing. However, there is still a need for a deeper quantitative analysis of the influence of asphalt concrete composition and technological factors on its properties. Traditional empirical approaches do not always allow us to identify nonlinear effects and interactions of factors. To solve this problem, it is advisable to use methods of mathematical modeling and statistical planning of the experiment.

Thus, modern literature demonstrates that improving the quality of road surfaces is possible only with the use of mathematical modeling and statistical analysis methods that take into account the nonlinear and interacting effects of technological and climatic factors. The present work continues these studies by offering a quantitative assessment of the effect of the composition and thermal hardening of the asphalt concrete mixture on its thermal conductivity and strength using the three-factor Box-Benken plan.

3 MATERIALS AND METHODS

Experimental Design and Factors. The study employed statistical modeling methods using the STATISTICA software environment. The experimental planning was carried out based on a three-level, three-factor Box-Behnken design. The selected factors were:

x_1 - temperature, °C (lower level 50°C, baseline 55°C, upper level 60°C). This factor represents the temperature conditions during the thermal processing of samples (simulating different compaction temperatures or heat-treatment durations).

x_2 - duration of thermal exposure, hours (minimum level 6 h, intermediate level 25.5 h, maximum level 48 h). This factor corresponds to the duration of sample thermostating (thermal strengthening) at the specified temperature. x_1.

x_3 - binder (bitumen) content in the mixture, % by mass. In the experiment, this factor was varied such that increasing the bitumen content decreased the gravel content, and vice versa. The low level corresponded to relatively low bitumen content (and high gravel content), whereas the high level corresponded to increased bitumen content. Note: For the "thermal conductivity" response, the primary contribution is expected from the mineral component (gravel), while for the «strength» response, it originates mainly from the bituminous binder. Thus, the factor is conditionally considered as «gravel/bitumen content» x_3 depending on the property being analyzed.

Thus, the Box-Behnken design included combinations of three factors at different levels. This fractional factorial design enables the evaluation of linear, quadratic, and interaction effects with a relatively small number of experiments. A total of 15 tests were performed, of which:

12 experiments corresponded to the main points of the design, where two of the three factors were varied sequentially, while the third factor was kept at its intermediate level. Four tests were conducted for each factor pair (two levels of one factor × two levels of the second factor at a fixed intermediate level of the third), resulting in:

x_1 and x_2 they vary with the average x_3: 2×2 = 4

x_1 and x_3 they vary with the average x_2: 2×2 = 4

x_2 and x_3 they vary with the average x_1: 2×2 = 4

Total: 4 + 4 + 4 = 12 experiments.

3 experiments were performed at the center point of the design (with all factors set at their intermediate levels). $x_1 = 55$ °C, $x_2 \approx 25{,}5$ ч, x_3 = average bitumen content) - to assess the reproducibility and adequacy of the model.

Measurable indicators (responses). Two responses were measured in each experiment:

y_1 - coefficient of thermal conductivity, W/(m·K). The measurements were carried out on asphalt concrete mortar samples using the laboratory steady-state heat flow method (standard guarded hot plate apparatus). Each sample was a prism measuring 50×50×50 mm, prepared from asphalt concrete mixtures of the specified composition. Thermal conductivity was measured at a temperature of 20±2°C in the dry state of the sample. The measurement error was estimated to be within ±5%.

y_2 - compressive strength, MPa. It was determined by the standard method of testing cubes of size 50×50×50 mm for axial compression. After thermal exposure, the samples were cooled to room temperature and tested using a hydraulic press at a constant loading rate. The strength was determined as the stress at the point of sample failure.

Materials. Standard road construction materials were used to prepare the samples: petroleum road bitumen grade BND 70/100 (or an equivalent in terms of viscosity), crushed stone from dense igneous rock (granite) with a fraction size of 5-10 mm, and mineral filler (limestone powder) for mix stabilization.

The mixture composition was selected to approximate the specifications of asphalt concrete type II, with a gravel-to-sand-to-mineral filler ratio of approximately 70:25:5 by mass at a baseline bitumen content of ~5.5%. During the experiment, the bitumen content was varied from ~5% (lower level) to ~6% (upper level), with corresponding adjustments to the gravel proportion.

Temperature x_1 was applied by heating the molds with compacted samples in a thermal chamber to the required temperature, while thermal exposure x_2 was achieved by maintaining the samples at this temperature for the specified duration . After thermal strengthening, the samples were removed and cooled to room temperature prior to testing and measurement of y_1 and y_2..

Data analysis. Based on the obtained experimental data, regression models were constructed for the response variables y_1 and y_2 (thermal conductivity and strength) as functions of the factors x_1, x_2, x_3. A second-order (quadratic) model was assumed to be adequate, which for each response variable takes the following form:

$$y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2 \quad (1)$$

where:
b_0 - intercept (constant term),
b_i -coefficients of the linear terms,
b_{ij} - coefficients of the two-way interaction terms,
b_{ii} - coefficients of the quadratic terms.

The coefficients b_i were estimated using the least squares method based on the 15 design points with the regression module of the STATISTICA software. The significance of each coefficient was tested through analysis of variance (ANOVA). For each factor and interaction, the calculated Fisher criterion (F-statistic) was determined.

$$F_{calculate} = \frac{SS_{factor}/DF_{factor}}{SS_{error}/DF_{error}} \quad (2)$$

where:
S - sum of squares of deviations,
DF_{factor} – degrees of freedom (df).

The obtained $F_{calculate}$ values where compared with the $F_{critical}$ value for the specified significance level (typically $\alpha = 0{,}05$). Based on the p-value, I was assessed whether the effects of the factors were statistically significant (if $p < 0{,}05$) or not. The coefficient of determination R^2 was also evaluated for the models of y_1 and y_2 and the absence of significant autocorrelation of residuals was verified.

Thermal resistance and frost penetration calculation. Alongside processing the experimental results, to interpret the thermal properties of asphalt concrete, the concept of layer thermal resistance was introduced. Thermal resistance R (m²·K/W) was determined as follows:

$$R = \frac{\delta}{\lambda}, \quad (3)$$

where:
δ - layer thickness (m),
λ - thermal conductivity of the material (Вт/(м·K)).

For a multilayer pavement structure, the total thermal resistance is equal to the sum of the resistances of the individual layers:

$$R_{total} = \sum \frac{\delta_i}{\lambda_i} \quad (4)$$

This concept is used in calculating the depth of ground frost penetration beneath the pavement structure. In the present study, knowing the thermal conductivity λ_i of asphalt concrete (the top layer) from the experiment, a theoretical calculation was performed to determine the seasonal frost penetration depth using a simplified method based on the heat balance principle. Additionally, approaches for determining the design soil moisture content in the frost zone were reviewed-this parameter is essential for assessing frost heave potential and the bearing capacity of the subgrade. Formulas from modern regulatory sources (**Karimov, 2020**) were used to calculate the design moisture content under various soil moisture conditions.

4 RESULTS AND DISCUSSION

Modeling of Thermal Conductivity and Strength. As a result of the statistical analysis, regression equations were obtained describing the dependence of y_1 (thermal conductivity) and $\mathbf{y_2}$ (strength) on the factors x_1, x_2, x_3. The determination coefficients of the models were $R^2_{y_1} \approx 0{,}88$ and $R^2_{y_2} \approx 0{,}96$, indicating sufficient accuracy of the experimental data approximation. The summarized results of the factor significance analysis are presented below.

4.1 Thermal conductivity

Thermal conductivity (y_1). The analysis of variance (ANOVA) showed that the most significant influence on the thermal conductivity coefficient is exerted by factor x_3 - the gravel content (inversely proportional to the bitumen content) in the mixture. As the proportion of the mineral filler increases, λ rises because gravel has higher thermal conductivity than bitumen. The effects of temperature (x_1) and thermal exposure duration (x_2) were statistically insignificant at the 5% significance level ($p > 0.05$), meaning their influence was negligible. In other words, within the range of 50-60°C and 6-48 hours, changes in these parameters did not result in a significant alteration of the thermal conductivity of the formed asphalt concrete. This is an important finding: the thermal conductivity of the material is primarily determined by its composition (structure and density), rather than by short-term thermal exposure regimes. The obtained regression equation for y_1 (in coded variables) includes a significant linear term for x_3 and minor quadratic adjustments for x_1 and x_2. Visualization of the model is presented as response profile graphs (**Figure 4**), where the curves confirm that changes in x_1 and x_2 are almost horizontal (minimal slope), whereas for x_3, a noticeable increase in y_1 is observed.

The experiments were conducted on dried samples, reflecting the thermal conductivity of the material in its dry state (λ_{dry}). In real-world conditions, asphalt concrete may contain a certain amount of moisture (especially in porous mixtures or after prolonged contact with water). Saturation of pores with water leads to an increase in the effective thermal conductivity coefficient, as heat transfer in the presence of water is more intensive than through air. According to the literature, moist asphalt concrete can exhibit a thermal conductivity coefficient 10-50% higher than that of the dry state, depending on the degree of saturation and porosity (**Rositsa&Penka, 2018**).

In particular, various authors have noted that for soils and road construction materials, when moisture content increases from 0 to 100% volumetric saturation, **λ** rises by approximately 1.5 times. In our study, the obtained range of values (λ_{dry}) for dry samples (around 0.6-0.8 W/m·K, depending on the composition) may increase to ~0.9-1.0 W/m·K under full water saturation of the pores. This must be considered in thermal calculations for pavements. On the other hand, the strength of asphalt concrete in the wet state usually decreases. Although a direct assessment of moist asphalt concrete strength was not performed in this study, it is known from experience and literature that water saturation and freeze-thaw cycles lead to strength losses of about 20-30% after several cycles. Therefore, when modeling the in-service performance characteristics, correction factors for moisture conditions should be introduced. In this article, we limited the scope to evaluating the influence of moisture on λ_{dry} and its implications for frost penetration calculations.

The obtained thermal conductivity values of the upper asphalt concrete layer were used to calculate the seasonal frost penetration depth of the soil beneath the pavement. The calculation was performed for a typical two-layer pavement structure: the upper layer-asphalt concrete, and the lower layer-crushed stone or sand-gravel material. The soil heat balance equation for the winter period was applied according to current regulations (Code of Practice of the Republic of Kazakhstan 3.03-19-2006). In accordance with this method, the frost penetration depth (h_f) is determined by the condition of equilibrium between the heat loss from the soil and the heat required to freeze a given soil volume. With known values of the thermal conductivity coefficients and layer thicknesses, the problem is solved iteratively. For simplification, calculations were performed using thermal resistance tables **(Lukashevich, 2020)**.

Example calculation: Two variants were considered: asphalt concrete as the pavement layer with a thickness of 0.05 m (5 cm):

(1) a coarse-grained mixture with high thermal conductivity - λ ≈ 0.72 W/m·K (approximately corresponding to a case with low bitumen content and high gravel content);

(2) a fine-grained sandy mixture with lower thermal conductivity - λ ≈ 0.62 W/m·K (more porous, with a higher bitumen content or added porous filler).

The underlying load-bearing layer-a crushed stone material-was 0.15 m thick, λ ≈ 1.5 W/m·K. The thermal conductivity of the soil (loam) was assumed to be 1.2 W/m·K.

According to the results of the thermal resistance calculation, the total resistance of the structure in the first variant was slightly lower: $R_{total} = 0{,}59$ (m²·K/W), compared to $R_{total} = 0{,}63$ (m²·K/W) in the second variant-due to the lower thermal conductivity of the top layer. The frost penetration depth under typical climatic conditions (accumulated freezing temperature of about 3000-3500°C·days) was approximately ~0.72 m in the first case and ~0.62 m in the second. Thus, reducing the thermal conductivity coefficient of asphalt concrete by ~14% (from 0.72 to 0.62) led to a reduction in frost penetration depth by about 10 cm (about 14% of the initial depth) compared to the higher thermal conductivity pavement. This result is consistent with expectations: a less thermally conductive layer better insulates the subgrade and reduces frost penetration. In practical terms, this means that using asphalt concrete mixtures with reduced thermal conductivity (e.g., high-porosity or with insulating additives) can be an effective method for protecting the roadbed from deep frost penetration. However, as noted, such solutions must be carefully balanced with strength requirements **(Chudinov et al., 2024)**.

Discussion of Results. The mathematical modeling performed confirmed the qualitative findings already familiar to road engineers and provided quantitative clarification. The strength of asphalt concrete, as expected, depends on the binder content and the compaction/exposure regime: more bitumen and longer exposure time result in a stronger mixture, although excessive bitumen is economically inefficient and may reduce the modulus of elasticity. Thermal conductivity, on the other hand, is primarily determined by the mineral framework and porosity: denser, gravel-rich mixtures conduct heat better, which can increase the frost penetration depth of the pavement during winter.

It is interesting to note that higher thermal conductivity of asphalt concrete is not always beneficial-in cold climates, it is actually desirable to have pavement with lower thermal conductivity to protect the subgrade from freezing **(Kovalev & Savukha, 2021)**. Conversely, very low thermal conductivity in summer can lead to overheating of the pavement surface and accelerated aging of the bitumen. Thus, the requirements for thermal conductivity are contradictory: in hot weather, it should dissipate heat; in cold weather, it should retain it. The optimal solution is likely a moderate thermal conductivity value or the use of specialized thermo regulating layers (e.g., insulating interlayers that keep the pavement cool in summer and warm in winter, as proposed by some researchers). Solving such problems is possible using optimization methods, including desirability criteria, which were implemented in the model **(Figures 1-4)**.

The practical value of the results lies in the fact that, by knowing the statistical relationships, the designer can predict how changes in the asphalt concrete mix design (for example, increasing the amount of bitumen or adding porous fillers) will affect its properties and the overall behavior of the pavement structure. The presented calculation example demonstrates that the choice of asphalt concrete mix type can alter the frost penetration depth of the subgrade by several tens of percent, which is comparable to the effect of layer thickness. Therefore, when designing pavements in regions with significant frost penetration, it is reasonable to consider not only the thickness of the layers but also the thermal conductivity of the materials as a design factor. This can be achieved either by adjusting the mix composition (e.g., using porous asphalt concrete as a thermal insulator) or by incorporating an insulating layer. Naturally, strength and wear resistance requirements of the pavement must also be satisfied simultaneously **(Tsytovich, 1973)**.

Finally, the strength results were experimentally validated: the trends obtained in the model (an increase in strength with higher bitumen content and longer thermal compaction time) correspond to the data from direct testing of the samples. This confirms the adequacy of the developed model and its potential use for predicting strength under other combinations of factors within the specified range.

It should be noted that, based on the modeling results, main effects plots and response surface graphs were constructed **(Figures 1-4)**. The influence of each factor on strength and thermal conductivity is presented through linear and quadratic components. It was established that the strength of the mixture increases with higher bitumen content and longer exposure time, with a pronounced nonlinear effect observed. Temperature also has an influence, but to a lesser extent. For thermal conductivity, the most significant factor is gravel content **(Figure 2)**, whereas the effects of temperature and exposure time were statistically insignificant ($p > 0.3$). The desirability surfaces **(Figures 3-4)** make it possible to identify the optimal region of factor combinations that ensure both high strength and sufficient thermal conductivity.

For a more detailed analysis of factor effects, the author performed ANOVA and evaluated the regression model coefficients for each response. Multi-criteria optimization of the responses was also conducted using the desirability function in the STATISTICA environment. The corresponding modeling results are presented below.

For a more detailed analysis of the factor effects, the author conducted an analysis of variance (ANOVA) and evaluated the regression model coefficients for each response variable. Additionally, multi-criteria optimization of the responses was performed using the desirability function within the STATISTICA environment.

Factor	ANOVA; Var.:Heat Insulation, W/m*K; R-sqr=,47589; Adj:,08281 (Аселя теплоизоляция) 3 3-level factors, 1 Blocks, 15 Runs; MS Residual=,0219519 DV: Heat Insulation, W/m*K				
	SS	df	MS	F	p
(1)Temperature, 0C L+Q	0,047254	2	0,023627	1,076303	0,385523
(2)Time, hour L+Q	0,030662	2	0,015331	0,698380	0,525349
(3)Gravel, % L+Q	0,087030	2	0,043515	1,982279	0,199882
Error	0,175615	8	0,021952		
Total SS	0,335075	14			

Figure 1 - ANOVA Analysis of Thermal Conductivity (author's material)

As shown in **Figure 1**, the ANOVA table for the thermal conductivity model (y_1) is presented. It is evident that none of the factors have a statistically significant effect on thermal conductivity at the 0.05 significance level: the Fisher (F) statistics for temperature, time, and gravel content are 1.076, 0.698, and 1.982, respectively, with p-values of 0.386, 0.525, and 0.200. The most noticeable influence is exerted by factor x_3 (gravel)-its combined effect (linear and quadratic) is slightly higher than the others, although it does not reach significance. The low R^2 ≈0,48 and R^2 ≈0,08 indicate that a substantial portion of the experimental data variability for thermal conductivity remains unexplained by this quadratic model.

Effect Estimates; Var.:Heat Insulation, W/m*K; R-sqr=,47589; Adj:,08281 (Аселя теплоизоляция)
3 3-level factors, 1 Blocks, 15 Runs; MS Residual=,0219519
DV: Heat Insulation, W/m*K

Factor	Effect	Std.Err.	t(8)	p	-95,% Cnf.Limt	+95,% Cnf.Limt	**Coeff.**	Std.Err. Coeff.	-95,% Cnf.Limt	+95,% Cnf.Limt
Mean/Interc.	0,726304	0,042843	16,95255	0,000000	0,627507	0,825100	0,726304	0,042843	0,627507	0,825100
(1)Temperature, 0C(L)	-0,088250	0,104766	-0,84235	0,424057	-0,329841	0,153341	-0,044125	0,052383	-0,164921	0,076671
Temperature, 0C(Q)	0,092625	0,077106	1,20127	0,264001	-0,085181	0,270431	0,046313	0,038553	-0,042591	0,135216
(2)Time, hour(L)	0,114250	0,104766	1,09052	0,307236	-0,127341	0,355841	0,057125	0,052383	-0,063671	0,177921
Time, hour(Q)	0,043286	0,077468	0,55875	0,591621	-0,135356	0,221928	0,021643	0,038734	-0,067678	0,110964
(3)Gravel, %(L)	0,190000	0,104766	1,81356	0,107304	-0,051591	0,431591	0,095000	0,052383	-0,025796	0,215796
Gravel, %(Q)	0,063375	0,077106	0,82192	0,434932	-0,114431	0,241181	0,031687	0,038553	-0,057216	0,120591

Figure 2 - Estimated Factor Effects for the Thermal Conductivity Model (author's material)

Figure 2 shows the effect estimates for the regression coefficients of the thermal conductivity model. The calculated factor effects (linear-L and quadratic-Q), standard errors, t-statistics, p-values, and 95% confidence intervals for the coefficient estimates are presented. As expected from the ANOVA results, none of the factor coefficients are statistically significant at the 0.05 level. Nevertheless, it can be noted that the largest effect in absolute terms is the linear component of gravel content (Effect = +0.190, p ≈ 0.107), which has a positive influence on thermal conductivity (i.e., increasing the gravel content raises thermal conductivity). The quadratic terms for all factors are small and statistically insignificant ($p > 0.26$), indicating the absence of a pronounced nonlinear response of y_1 within the studied factor range. Thus, changes in temperature and exposure time have virtually no effect on thermal conductivity, whereas increasing the gravel proportion may slightly raise its value **(Rehab et al.,2018)**.

The next step involved multi-criteria optimization of the responses (y_1 and y_2) using the desirability function method. The optimization criteria were selected as maximizing strength while simultaneously ensuring sufficient thermal conductivity. For each response, a desirability function was defined: $d_1(y_1)$ and $d_2(y_2)$, normalized within the range [0; 1] (0 - unsatisfactory value, 1 - best achievable value). The overall desirability D was calculated as the geometric mean:

$$D = \sqrt[n]{d_1(y_1) \cdot d_2(y_2) \dots d_n(y_n)} \quad (4)$$

with n = 2 in this case.

As a result, response and desirability profiles were obtained for each factor (**Figure 3**), as well as desirability surfaces on the factor plane.

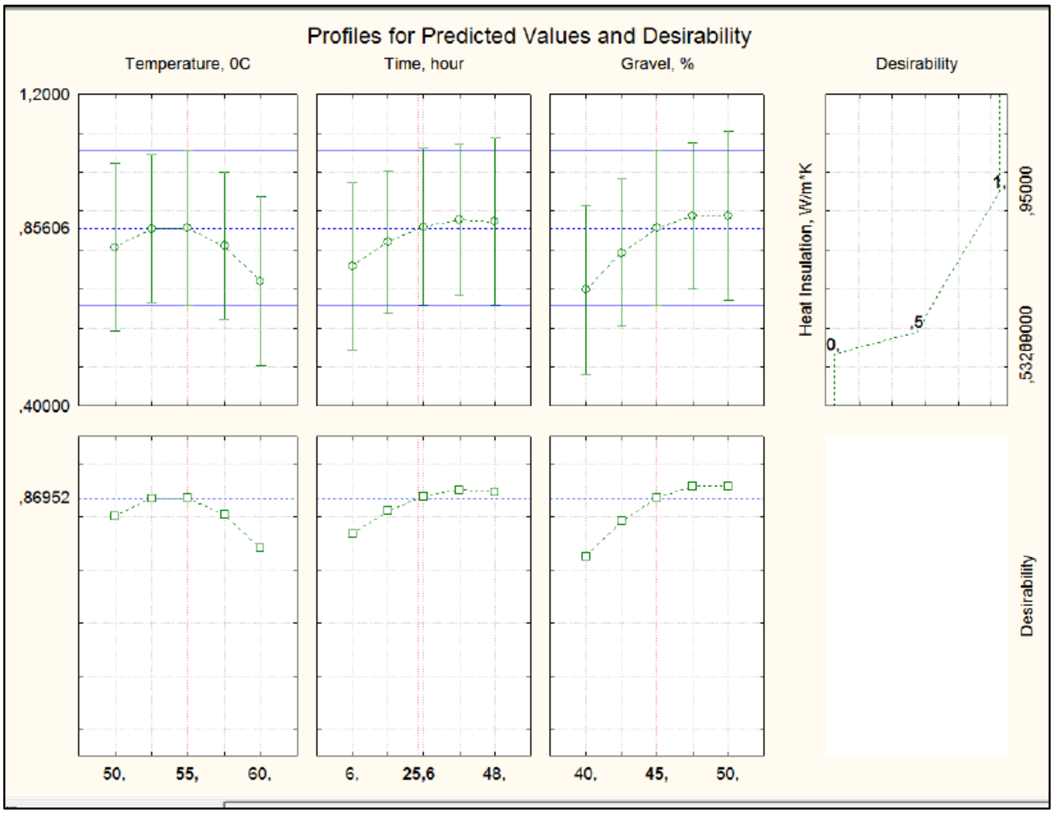

Figure 3 - Response and Desirability Profiles for Thermal Conductivity (y_1) as a Function of Factors x_1,x_2,x_3 (author's material)

Figure 3 shows the profiles of changes in the predicted thermal conductivity values and the corresponding desirability coefficient d_1 when varying each factor (x_1: temperature, x_2: time, x_3: gravel content). Vertical red lines indicate the position of the optimal factor combination identified through optimization. Horizontal lines indicate the baseline response level and boundary values. The graphs show that factor x_3 (gravel content) has the strongest influence on thermal conductivity: as the gravel content increases, desirability d_1 rises because thermal conductivity approaches the desired high value. In contrast, changes in temperature and time have virtually no effect on thermal conductivity (the y_1 curves are relatively flat), corresponding to the weak effects of $x_1 and\, x_2$ identified earlier **(Figure 4)**.

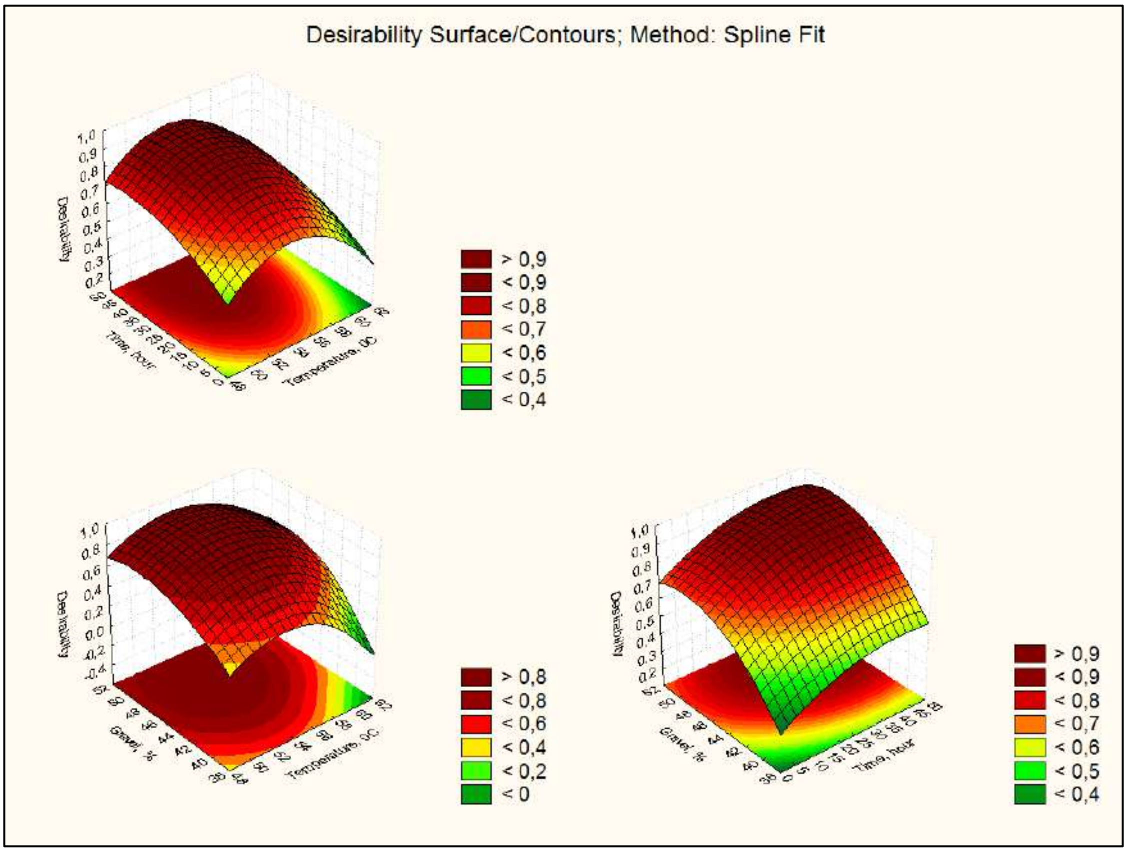

Figure 4 - 3D Surfaces of the Desirability Function D on Factor Combination Planes (author's materials)

4.2 Strength

Strength (y_2). Unlike y_2, for asphalt concrete strength, all three considered factors were significant. The greatest contribution to strength variation comes from bitumen content (x_3): as the percentage of bitumen increases, compressive strength rises monotonically. This is explained by the fact that higher bitumen content improves bonding between mineral particles and reduces overall porosity, leading to increased sample strength. The exposure time factor (x_2) also positively influences strength-extended thermal exposure (up to 48 hours) promotes structuring of the bitumen film and additional material hardening, especially at elevated temperatures. A pronounced nonlinear effect of time was observed: the strength gain slows down when moving from 25 h to 48 h. Temperature (x_1) showed a smaller but still statistically significant effect: moderate increases in processing temperature also contributed to strength improvement; however, this effect appears in combination with other factors. ANOVA revealed a high statistical significance of x_3 and x_2 ($p < 0.001$) and a somewhat weaker but still significant effect for x_3 and x_1 ($p \approx 0.04$). In **Figure 6**, the steepness of the main effect curves can be seen: the curves for x_3 and $x_2$have a pronounced slope, while for $\mathbf{x_1}$ the slope is less steep. Thus, the strength of the mixture is primarily determined by bitumen content and thermal exposure, especially when bitumen content is sufficiently high.

Factor Interactions. The y_2 model revealed certain interactions; for example, the effect of temperature (x_1) becomes more pronounced at high bitumen content (x_3)-apparently, increasing the temperature accelerates structuring within the bitumen-rich mixture. Meanwhile, the interaction between x_1 and x_2 turned out to be insignificant: increasing exposure time at higher temperatures was practically equivalent to that at lower temperatures, meaning the effects are essentially additive.

The quadratic terms in the y_2 model indicate the presence of an optimum: excessive bitumen content may slightly reduce strength due to excessive softening of the structure; however, within the studied range of 5-6%, this was not observed (strength continued to increase up to the highest tested x_3 level).

For y_1, the quadratic term for x_3 showed a slight curvature of the $\lambda(x_3)$ relationship, which is associated with the fact that, at high gravel content, the increase in thermal conductivity starts to slow down (once it reaches the thermal conductivity level of the mineral aggregate itself, further increases in gravel content have little effect) **(Pengyu & Hao, 2022)**.

The modeling results are summarized in graphical form in **Figures 5-8**. **Figure 5** shows the effect of each factor on strength (main effect profiles), while **Figure 2** shows the effect on thermal conductivity. **Figures 7-8** illustrate the 3D desirability surfaces-combinations of factors that simultaneously optimize both responses. The optimum region is found at relatively high values of x_3 (bitumen ~6%) and x_2 (~40-48 h), and moderate x_1 (~55°C); in this region, a compromise is achieved between maximum strength and sufficient (not too high) thermal conductivity of the material.

It should be noted that targeted modification of asphalt concrete's thermal conductivity is possible through adjusting porosity and mix composition-for example, by introducing porous fillers or special additives. However, this may lead to a reduction in strength, so optimization is required. The developed models and response surfaces help identify a balanced combination of properties.

ANOVA; Var.:Strength, MPa4; R-sqr=,97944; Adj:,96402 (Spreadsheet10)
3 3-level factors, 1 Blocks, 15 Runs; MS Residual=1,475655
DV: Strength, MPa4

Factor	SS	df	MS	F	p
(1)Temperature, 0C L+Q	63,6496	2	31,8248	21,5666	0,000599
(2)Time,hour L+Q	201,0240	2	100,5120	68,1135	0,000009
(3)Bitumen, % L+Q	257,3415	2	128,6707	87,1957	0,000004
Error	11,8052	8	1,4757		
Total SS	574,1088	14			

Figure 5 - ANOVA Analysis of Strength (author's materials)

Figure 5 presents the ANOVA table for the strength model (y_2). Unlike thermal conductivity, all three factors for strength were statistically significant ($p < 0.001$). The largest contribution to strength variation is made by bitumen content (factor x_3): F = 87.20, p ≈ 0.000004. The influence of exposure time (x_2) was also highly significant (F = 68.11; p ≈ 0.000009). Temperature (x_1) had a somewhat smaller but still significant effect (F = 21.57; p ≈ 0.0006). The high R^2 (≈0,979) and adjusted R^2 (≈0,964) indicate that the selected model describes the variability of strength in the experiment well.

Effect Estimates; Var.:Strength, MPa4; R-sqr=,97944; Adj:,96402 (Spreadsheet10)
3 3-level factors, 1 Blocks, 15 Runs; MS Residual=1,475655
DV: Strength, MPa4

Factor	Effect	Std.Err.	t(8)	p	-95,% Cnf.Limt	+95,% Cnf.Limt	Coeff.	Std.Err. Coeff.	-95,% Cnf.Limt	+95,% Cnf.Limt
Mean/Interc.	8,35976	0,353087	23,6762	0,000000	7,54554	9,17398	8,35976	0,353087	7,54554	9,17398
(1)Temperature, 0C(L)	1,39975	0,858969	1,6296	0,141840	-0,58104	3,38054	0,69988	0,429484	-0,29052	1,69027
Temperature, 0C(Q)	-4,02208	0,632184	-6,3622	0,000218	-5,47990	-2,56426	-2,01104	0,316092	-2,73995	-1,28213
(2)Time,hour(L)	-1,55275	0,858969	-1,8077	0,108272	-3,53354	0,42804	-0,77637	0,429484	-1,76677	0,21402
Time,hour(Q)	-7,40049	0,635154	-11,6515	0,000003	-8,86516	-5,93583	-3,70025	0,317577	-4,43258	-2,96791
(3)Bitumen, %(L)	0,80950	0,858969	0,9424	0,373568	-1,17129	2,79029	0,40475	0,429484	-0,58564	1,39514
Bitumen, %(Q)	8,42835	0,641237	13,1439	0,000001	6,94966	9,90705	4,21418	0,320619	3,47483	4,95352

Figure 6 - Estimated Factor Effects for the Strength Model (author's materials)

Figure 6 presents the effect estimates for the coefficients of the strength model. Unlike thermal conductivity, significant nonlinear (quadratic) factor effects are observed for strength. The quadratic effect of bitumen content is particularly large: Effect = +8.4285, p ≈ 0.000001, 95% CI [6.95; 9.91]. The positive sign of the quadratic term for x_3 indicates that the dependence of strength on bitumen content has a curved shape with an extremum (minimum) near the center of the factor's range; in practice, strength maximizes when the bitumen content deviates from the plan center.

Similarly, the significant negative quadratic effect of exposure time (Effect = -7.4005; p ≈ 0.000003) indicates a curved influence of x_2 (strength decreases at too long or too short exposure times, peaking at an intermediate value). The quadratic effect of temperature is also statistically significant and negative (Effect = -4.0221, p ≈ 0.0002), indicating the presence of an optimal temperature range for mixture hardening.

The linear components of the factors for strength are less significant: for example, the linear effect of bitumen content is small (Effect = +0.8095, p ≈ 0.374) compared to the quadratic term-this suggests the presence of an optimum strength at a certain bitumen content. The linear effect of exposure time (-1.5528, p ≈ 0.108) is also less pronounced than the quadratic, and the temperature effect (+1.3998, p ≈ 0.142) is close to the threshold of significance.

Overall, the coefficient estimates confirm the conclusion that strength exhibits a pronounced extremum in the region of central factor levels, especially in relation to bitumen content and exposure time (**Zicheng et al., 2022**).

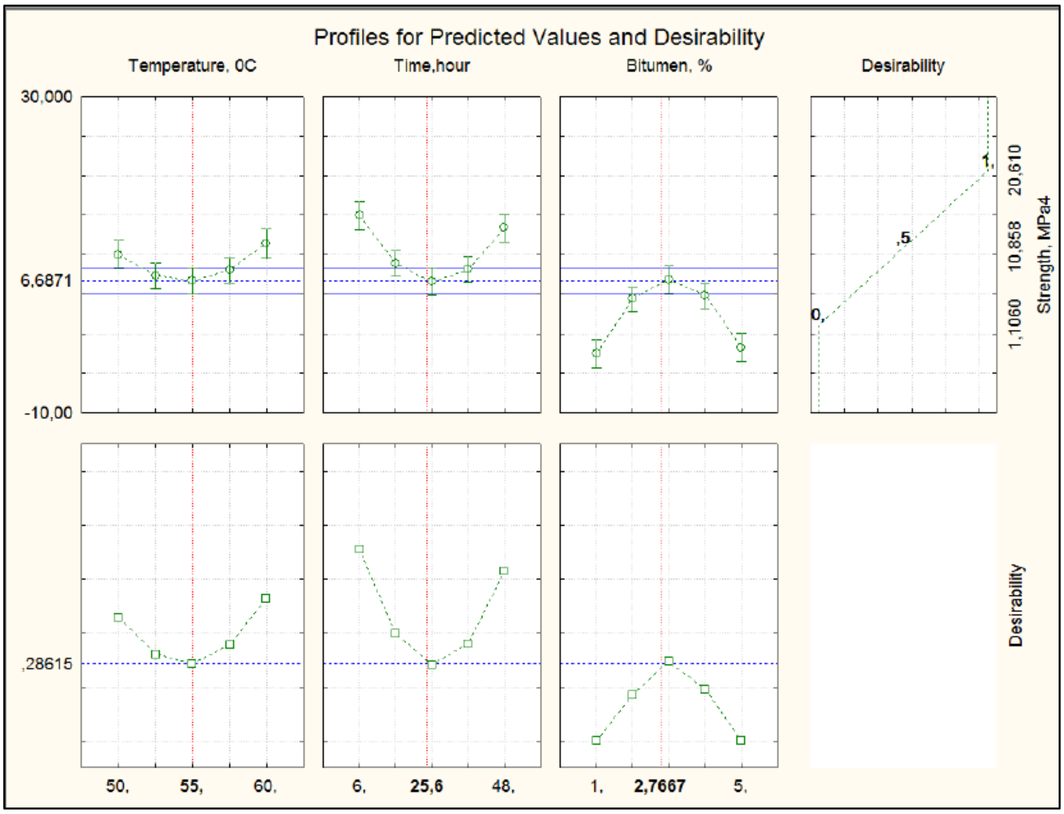

Figure 7 - Response and Desirability Profiles for Strength (y_2) as a Function of Factors ($x_3 - x_1$) (author's materials)

Figure 7 similarly presents the profiles for strength and the desirability function d_2. In this case, factor **x₃** (bitumen content) has a decisive impact on strength: when bitumen content is too low or too high, strength decreases and the desirability coefficient d_2 drops. The maximum desirability is achieved at an intermediate bitumen content (~4-5%), which corresponds to the optimal strength value. Exposure time (d_2) also plays a significant role: as time increases from 6 to ~25 hours, strength rises, increasing d_2; however, further increases in exposure time up to 48 hours may lead to a slight reduction in strength (a nonlinear effect). Temperature (x_1) influences strength to a lesser extent, with the d_2 optimum occurring around 55°C. Thus, the profiles confirm that to achieve maximum strength, a moderate temperature, sufficient exposure time, and optimal bitumen content are required (**Jiaqi et al., 2022**).

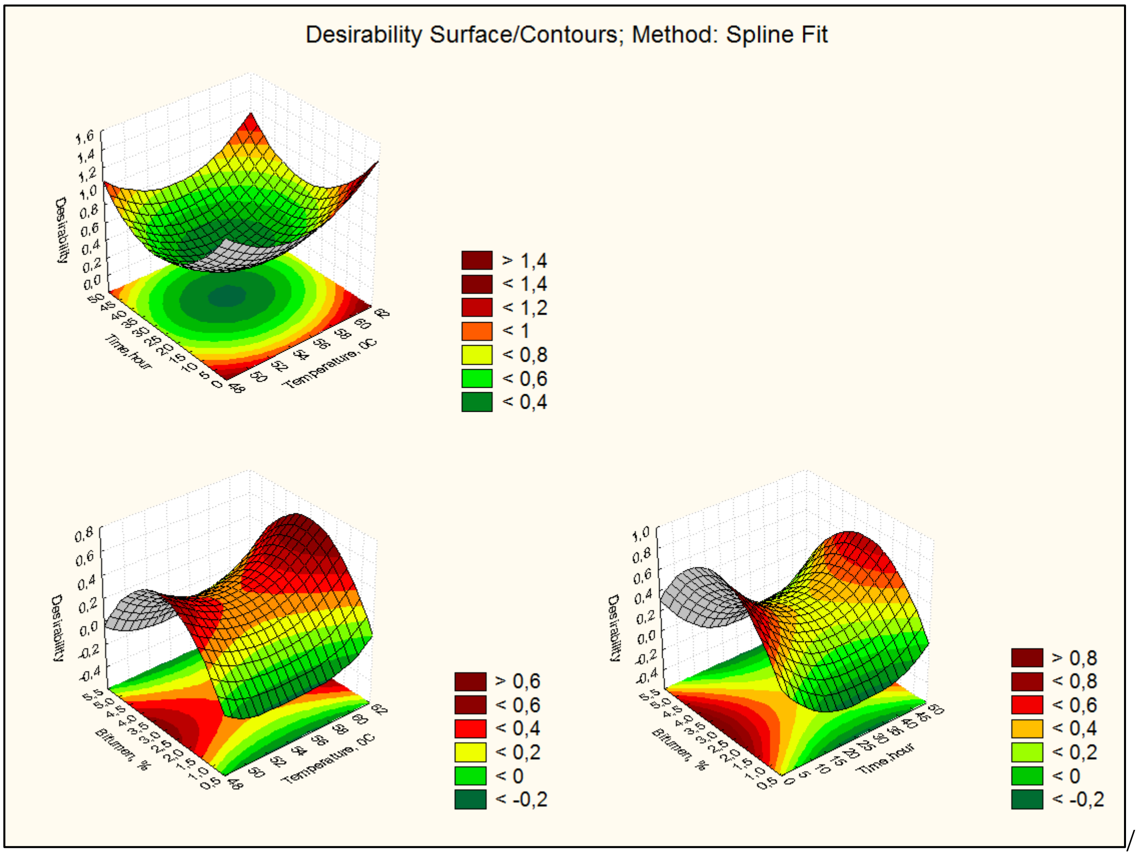

Figure 8 - 3D Surfaces of the Desirability Function D on Factor Combination Planes [author's materials].

The overall desirability function D reaches a maximum value close to 1 in the region of optimal parameters. Figure 8 shows the 3D surfaces and desirability contours in the factor coordinate planes: (a) temperature-time, (b) temperature-bitumen content, (c) time-bitumen content. The color scale reflects the level of D (from dark green for D < 0.7 to dark red for D > 0.9). It can be seen that the D > 0.9 region is formed at temperatures around 55°C, exposure times of approximately 25-30 hours, and bitumen content around 4-5%. In particular, the optimal combination of factors for maximizing D corresponds to the following values: temperature ~55°C, time ~26 h, bitumen content ~4.5% (with fixed gravel content as part of the mix). Under these parameters, high strength (~11 MPa) is achieved with satisfactory thermal conductivity (~0.85 W/m·K), corresponding to $D \approx 0.95$. Thus, the use of the desirability function made it possible to determine a compromise region that satisfies both quality criteria.

5 CONCLUSIONS

1. The strength of the asphalt concrete mixture depends primarily on bitumen content (within the studied range of 5-6% by mass) as well as on the duration of thermal exposure at a given temperature. Increasing the binder content and exposure time leads to higher strength; the effect of compaction temperature is less significant, although raising the temperature to 60°C slightly improves strength.
2. The thermal conductivity of asphalt concrete is mainly determined by the mineral content (gravel) and the mixture's porosity. Denser, gravel-rich mixtures have higher thermal conductivity. The influence of other factors (temperature and preparation time) is statistically insignificant for the thermal conductivity of the dry material. However, water saturation significantly increases its thermal conductivity, which should be considered during service.
3. Three-factor modeling using a Box-Behnken design and analysis of variance (ANOVA) made it possible to quantitatively assess factor effects and identify nonlinear dependencies. Regression

response equations, factor influence profiles, and property optimum regions were constructed. The use of the desirability criterion showed that optimizing the mixture to achieve maximum strength with acceptable thermal conductivity is accomplished with increased bitumen content (~6%) and sufficient thermal strengthening time (>40 h).

4. The thermal analysis confirmed that reducing the thermal conductivity of the asphalt concrete layer decreases the frost penetration depth of the subgrade, which is beneficial for preventing frost heave. The determination of the design soil moisture content (considering the type of moisture exposure) showed that even in arid conditions, moisture in the frost zone can reach 65-80% of the soil's liquid limit, which, in the absence of sufficient insulation, may cause heaving. The results obtained can be used in the design of asphalt concrete mixtures with specified characteristics and in comprehensive pavement design calculations for frost resistance.

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RESEARCH ARTICLE

EFFECT OF ANNEALING TEMPERATURE AND ATMOSPHERE ON THE PROPERTIES POROUS SIO_2–SIC CERAMICS

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Abstract. *This study investigates the influence of annealing at 1000 °C for 1 h in argon and air atmospheres on the microstructure and properties of porous SiO_2–SiC ceramics containing 0–35 wt% nano-SiC. The porosity increased slightly with the addition of nano-SiC, from 75.2 % to 76.0 % for samples annealed in argon, and from 64.8 % to 67.5 % for those treated in air. The higher porosity in the air-annealed specimens is attributed to partial oxidation of SiC, which produces gaseous by-products that promote pore formation. Thermal conductivity decreased from 0.152 to 0.122 W m^{-1} K^{-1} in the argon series and from 0.058 to 0.045 W m^{-1} K^{-1} in the air series, owing to enhanced phonon scattering by pores and oxidation-derived SiO_2 layers. Compressive strength showed the opposite trend, declining from 24.8 to 14.1 MPa in argon and from 10.6 to 4.0 MPa in air as SiC content increased. These results demonstrate that annealing atmosphere strongly affects pore evolution, oxidation behavior, and interfacial bonding, thus controlling the balance between thermal insulation and mechanical stability in porous SiO_2–SiC ceramics.*

Keywords: *porous ceramics; SiO_2–SiC composites; annealing atmosphere; thermal conductivity; compressive strength*

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КЕУЕКТІ SiO_2–SIC КЕРАМИКАСЫНЫҢ ҚАСИЕТТЕРІНЕ КҮЙДІРУ ТЕМПЕРАТУРАСЫ МЕН АТМОСФЕРАСЫНЫҢ ӘСЕРІ

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Аңдатпа. *Бұл зерттеу 1000 °C температурада 1 сағат бойы аргон және ауа атмосфераларында өткізілген күйдірудің 0–35 мас.% нано-SiC қамтылған кеуекті SiO_2–SiC керамикасының микроқұрылымы мен қасиеттеріне әсерін қарастырады. Нано-SiC мөлшері артқан сайын кеуектілік сәл өсті: аргонда күйдірілген үлгілерде — 75,2 %-дан 76,0 %-ға дейін, ал ауада өңделген үлгілерде — 64,8 %-дан 67,5 %-ға дейін. Ауада күйдірілген үлгілердің кеуектілігінің жоғары болуы SiC-тің жартылай тотығуымен және кеуек түзілуін күшейтетін газ тәрізді өнімдердің бөлінуімен түсіндіріледі. Жылуөткізгіштік аргон сериясында 0,152-ден 0,122 Вт/м·К-ге дейін және ауа сериясында 0,058-ден 0,045 Вт/м·К-ге дейін төмендеді, бұл фонондардың кеуек беттерінде шашырауы мен SiO_2 тотығу қабаттарының түзілуімен байланысты. Қысу беріктігі керісінше төмендеді: аргонда 24,8-ден 14,1 МПа-ға, ауада 10,6-дан 4,0 МПа-ға дейін. Нәтижелер күйдіру атмосферасының кеуек эволюциясына, тотығу процестеріне және фазааралық байланыстарға айтарлықтай әсер ететінін, осылайша кеуекті SiO_2–SiC керамикасының жылуоқшаулау мен механикалық тұрақтылық арасындағы тепе-теңдікті басқаратынын көрсетеді.*

Түйін сөздер: *кеуекті керамика; SiO_2–SiC композиттері; күйдіру атмосферасы; жылуөткізгіштік; сығылу беріктігі.*

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НАУЧНАЯ СТАТЬЯ

ВЛИЯНИЕ ТЕМПЕРАТУРЫ И АТМОСФЕРЫ ОТЖИГА НА СВОЙСТВА ПОРИСТОЙ КЕРАМИКИ SIO_2–SIC

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Аннотация. *В данной работе исследовано влияние отжига при 1000 °C в течение 1 ч в атмосфере аргона и воздуха на микроструктуру и свойства пористой керамики на основе SiO_2–SiC, содержащей 0–35 мас.% нано-SiC. С увеличением содержания нано-SiC пористость несколько возрастала: с 75,2 % до 76,0 % для образцов, отожжённых в аргоне, и с 64,8 % до 67,5 % для образцов, обработанных в воздухе. Более высокая пористость при отжиге в воздухе связана с частичным окислением SiC, сопровождающимся выделением газообразных продуктов, способствующих образованию пор. Теплопроводность уменьшалась с 0,152 до 0,122 Вт/м·К в серии, отожжённой в аргоне, и с 0,058 до 0,045 Вт/м·К в серии, обработанной в воздухе, что объясняется усиленным рассеянием фононов на порах и образованием оксидных слоёв SiO_2. Прочность при сжатии, напротив, снижалась с 24,8 до 14,1 МПа в аргоне и с 10,6 до 4,0 МПа в воздухе при увеличении содержания SiC. Полученные результаты показывают, что атмосфера отжига существенно влияет на эволюцию пор, процессы окисления и межфазное взаимодействие, определяя соотношение между теплоизоляционными и механическими свойствами пористой керамики SiO_2–SiC.*

Ключевые слова: *пористая керамика; композиты SiO_2–SiC; атмосфера отжига; теплопроводность; прочность при сжатии*

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CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

The authors declare that no generative artificial intelligence technologies or AI-based tools were used in the preparation of this article.

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.

Авторлар мақаланы дайындау барысында генеративті жасанды интеллект технологиялары мен жасанды интеллектке негізделген технологияларды пайдаланбағанын 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.

Авторы заявляют о том, что при подготовке статьи не использовались технологии генеративного искусственного интеллекта и технологии, основанные на искусственном интеллекте.

1 INTRODUCTION

Porous ceramics have become an essential class of advanced materials due to their unique combination of low density, high thermal stability, and chemical inertness, which make them suitable for use in extreme environments. These materials are widely employed in high-temperature thermal insulation, catalyst supports, filtration membranes, refractory linings, and energy-efficient construction systems **(She et al., 2003)**. Their microstructure, consisting of interconnected pores within a rigid ceramic matrix, provides a balance between mechanical integrity and desired functional properties such as low thermal conductivity and high permeability **(Dey et al., 2011)**. The key advantage of porous ceramics lies in their ability to maintain dimensional and chemical stability at temperatures exceeding 1000 °C while exhibiting adjustable porosity levels and lightweight characteristics.

Among various porous ceramic systems, silicon carbide (SiC) and silicon dioxide (SiO_2) based composites stand out for their synergistic combination of thermal and mechanical properties. SiC possesses outstanding characteristics such as high hardness, strong covalent bonding, superior thermal conductivity (~120 W m^{-1} K^{-1} for dense SiC), and excellent oxidation resistance at elevated temperatures **(Yuan et al., 2016)**. Conversely, SiO_2 offers low intrinsic thermal conductivity (~1.4 W m^{-1} K^{-1}), a relatively low sintering temperature, and good processability, making it a valuable component for forming porous structures **(Yuan et al., 2016a)**. When combined, the SiO_2–SiC composite system integrates the thermal insulation capability of silica with the thermal stability and mechanical robustness of SiC, yielding a promising material for next-generation thermal barrier and insulating applications **(Kim et al., 2005)**.

In porous SiO_2–SiC ceramics, microstructural evolution during fabrication and subsequent heat treatment plays a decisive role in determining final performance. The microstructure is governed by factors such as sintering temperature, time, particle size, and most critically, the annealing atmosphere **(Jana et al., 2017)**. During thermal treatment, SiC particles can undergo partial oxidation. This reaction leads to the formation of a thin SiO_2 layer on SiC surfaces and the generation of gaseous carbon oxides that contribute to increased porosity **(Wan & Wang, 2018)**. Therefore, oxidation processes under air or oxygen-rich environments can substantially modify pore morphology, interparticle bonding, and phase composition. In contrast, in inert atmospheres such as argon, oxidation is suppressed, and the resulting microstructure depends more on viscous flow and particle rearrangement. These mechanisms yield distinct structural features that directly influence both thermal conductivity and mechanical strength **(Chen &Miyamoto, 2014)**.

The relationship between porosity and thermal transport in ceramics is well-documented. The introduction of pores disrupts the phonon transport path, reducing the effective thermal conductivity due to enhanced phonon scattering at solid-pore interfaces **(Chun et al., 2005)**. However, excessive porosity can severely weaken mechanical strength, as the load-bearing cross-section is reduced and stress concentration arises around pores **(Kim et al., 2020, Wan & Wang, 2018)**. Thus, an optimal microstructure must balance porosity for insulation and sufficient strength for mechanical stability. The addition of nano-SiC particles is particularly interesting because nano-sized SiC can alter sintering behavior, influence pore evolution, and improve interfacial bonding at moderate temperatures **(Su et al., 2018)**. At the same time, nanoscale SiC may also promote heterogeneous oxidation and interfacial phonon scattering, leading to additional reductions in thermal conductivity **(Streitwieser et al., 2005)**. Annealing, or controlled post-sintering heat treatment, is a powerful technique to modify ceramic microstructure without significant changes in composition. The annealing atmosphere is especially critical: an inert gas such as argon limits oxidation and helps preserve SiC integrity, while an oxidizing atmosphere (air) induces surface oxidation, forming SiO_2-rich layers that can seal pores or, alternatively, generate new ones depending on the oxidation kinetics.

Studies have demonstrated that annealing at intermediate temperatures (900–1200 °C) under air results in the gradual oxidation of SiC, generating amorphous SiO_2 films that may enhance the overall insulating capability but reduce strength due to interfacial debonding **(Malik et al., 2020)**. In contrast, annealing under argon tends to stabilize the as-formed microstructure and preserve mechanical properties. Although individual effects of oxidation and porosity on SiC and SiO_2 ceramics have been widely reported, comparative studies analyzing the interplay of annealing atmosphere and nano-SiC content in SiO_2–SiC composites remain limited. Recent reports on hierarchical porous ceramics have suggested that the combined use of nano-sized reinforcements and tailored annealing conditions can yield materials with both ultralow thermal conductivity (< 0.06 W m^{-1} K^{-1}) and acceptable compressive strength (> 10 MPa) **(Jana et al., 2017)**. However, achieving this balance requires a clear understanding of how pore morphology, oxidation reactions, and interfacial phenomena evolve under different atmospheres. Furthermore, the growing demand for lightweight insulation materials in aerospace, energy, and environmental technologies underscores the need for ceramics that combine low thermal conductivity with sufficient mechanical robustness. For instance, in gas turbines and combustion systems, thermal barriers must resist temperatures beyond 1000 °C while maintaining dimensional stability. In energy storage and conversion systems, such as solid oxide fuel cells, materials with tailored porosity are needed to minimize thermal losses while ensuring structural integrity. The SiO_2–SiC system provides an adaptable platform for these applications, but systematic studies under well-controlled annealing conditions are required to optimize its potential.

Therefore, the present study investigates the effect of annealing at 1000 °C for 1 h in argon and air atmospheres on the porous SiO_2–SiC ceramics with varying nano-SiC contents (0–35 wt%). The focus is on elucidating the interrelation between porosity, microstructure, thermal conductivity, and compressive strength. By comparing inert and oxidizing annealing environments, this work aims to reveal the mechanisms that govern microstructural evolution and property variations in SiO_2–SiC composites. The findings will contribute to the rational design of low-thermal-conductivity porous ceramics with optimized performance for high-temperature insulation and energy applications.

2. LITERATURE REVIEW

Porous SiC and SiC-based composite ceramics have been studied extensively. **Malik et al., (2020)** observed that both thermal conductivity and mechanical strength tend to decrease as porosity increases, though particle size and intergranular bonding can modulate this trend. **Kang et al. (2021)** reported extremely low thermal conductivities in porous nano-SiC via multiple thermal resistance engineering.

In the specific SiO_2–SiC system, oxidation of SiC to SiO_2 can act as a sintering aid, modifying microstructural connectivity and pore geometry **(Gomez-Gomez et al., 2019).** The interfacial thermal boundary resistance between SiO_2 and SiC phases can further suppress phonon transport **(Manoji Kumar et al., 2011)**. Recent work on hierarchical porous ceramics combining SiC and oxide phases has shown promising insulation properties.

However, there is a lack of studies focusing specifically on how annealing atmosphere (Ar vs. air) at moderate temperatures (e.g. 1000 °C) influences the tradeoff between thermal insulation and mechanical strength in SiO_2–SiC composites. This gap motivates the present work.

3. MATERIALS AND METHODS

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 800 °C for 2 h, then subsequently annealed at 1000 °C for 1 h in air and argon atmosphere.

The sintered specimens were designated as follows: for example, SA-10 and SAr-10, where the number after the dash (10) indicates the sintering temperature of 1000 °C, A and Ar means air and argon atmosphere, respectively.

The theoretical density of the porous SiO_2-SiC ceramics was calculated using the rule of mixtures according to the following formula:

$$\rho_{th} = \rho_{\mathrm{SiO_2}} V_{\mathrm{SiO_2}} + \rho_{SiC} V_{SiC} \quad (1)$$

where, $\rho_{\mathrm{SiO_2}}$ and ρ_{SiC} are the theoretical densities of silica 2.196 (gcm^{-3}) and SiC (3.216 gcm^{-3}), respectively. $V_{\mathrm{SiO_2}}$ 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.

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.

4 RESULTS AND DISCUSSION

4.1 Porosity and Microstructure

Figure 1 shows the porosity of the porous SiO_2-SiC based ceramics as a function of initial nano-SiC content. With increasing SiC content, porosity of argon-annealed samples increased from 75.2 % to 76.0 %, while for air-annealed samples it increased from 64.8 % to 67.5 %. The porosity of argon-annealed porous SiO_2-SiC based ceramics were 75.2% for SAr0-10, 75.7% for SAr10-10, 75.8% for SAr20-10, and 76.0% for SAr35-10.

In argon atmosphere, the increase is modest; presence of SiC particles impedes viscous flow of SiO_2 and densification, thus stabilizing the pore network. In air, oxidation of SiC leads to the formation of additional SiO_2 and gaseous CO/CO_2, which expands the pore volume and introduces new pore channels, thus boosting porosity more noticeably.

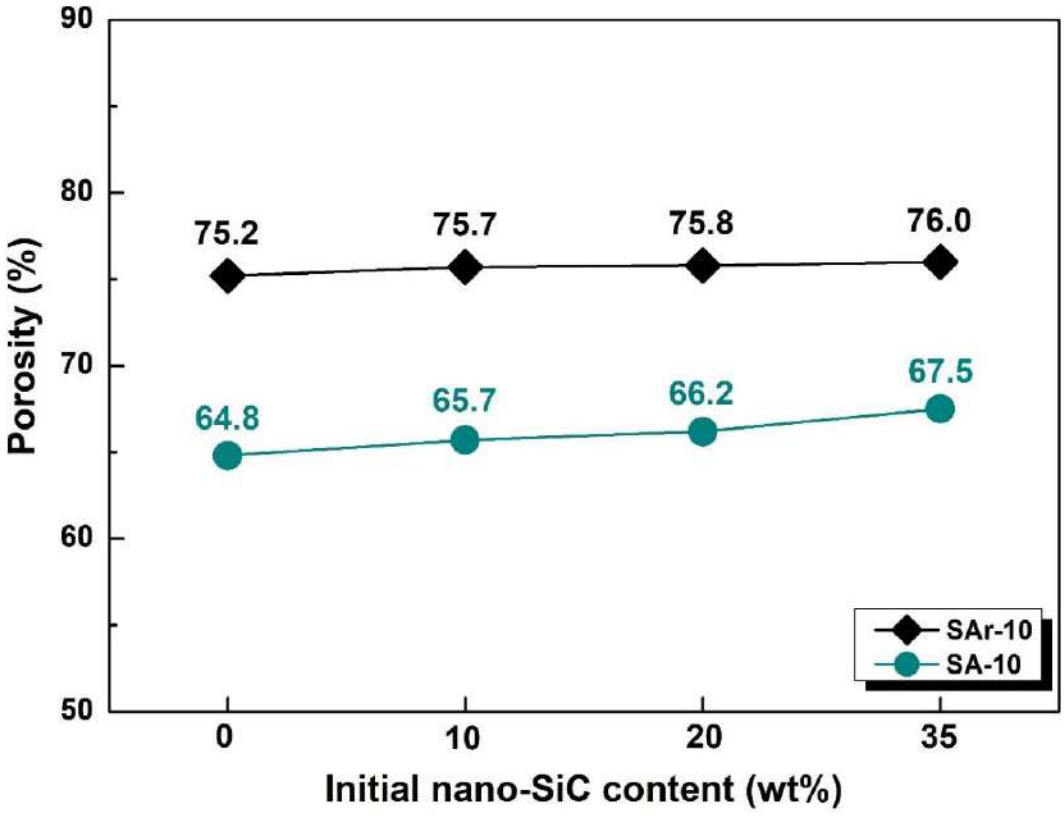

Figure 1 – Porosity of the porous SiO_2-SiC based ceramics as a function of initial nano-SiC content.

4.2 Thermal conductivity

The thermal Conductivity of the porous SiO_2-SiC based ceramics as a function of initial nano-SiC content has shown in **Figure 2**. Porous SiO_2-SiC based ceramics annealed in argon atmosphere showed the decrease in thermal conductivity from 0.152 – 0.122 W m^{-1} K^{-1} when initial nano-SiC content increased from 0 to 35 wt%. The thermal conductivity of air-annealed porous SiC ceramics decreased from 0.058 → 0.045 W m^{-1} K^{-1} as initial nano-SiC content increases from 0 to 35 wt%.

The marked decrease of thermal conductivity correlates with increased porosity and disruption in continuous conduction paths. The air-annealed samples show much lower conductivity, reflecting both the higher porosity and enhanced phonon scattering at interfaces, including possible amorphous SiO_2 layers formed via oxidation. The role of thermal boundary resistance between SiO_2 and SiC phases becomes more significant in these mixed-phase porous systems.

Compared to literature, the conductivity range is competitive with other low-k porous systems (**e.g., Kang et al. 2021**, 0.14 W m^{-1} K^{-1}) or the composite SiC–SiO_2–Al_2O_3–TiO_2 system achieving ~0.059 W m^{-1} K^{-1} at ~74% porosity.

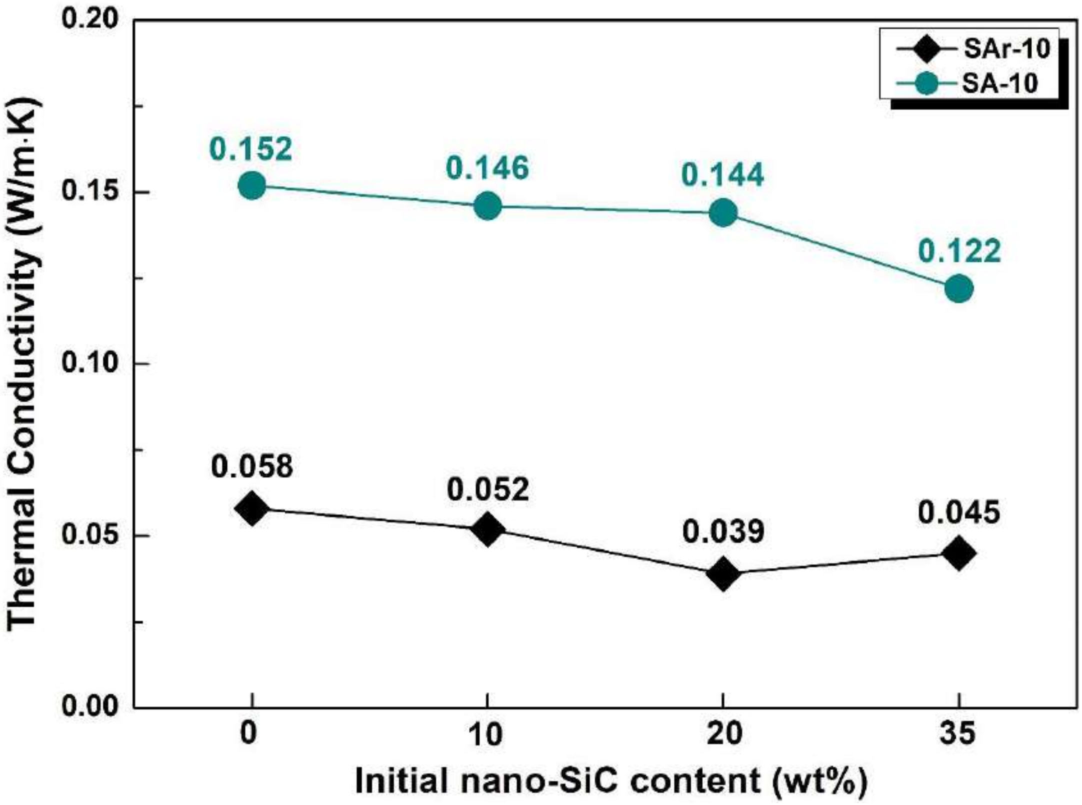

Figure 2 – Thermal Conductivity of the porous SiO_2-SiC based ceramics as a function of initial nano-SiC content.

4.3 Compressive strength

Compressive strengths decrease as initial nano-SiC content increases **(Figure 3)**. Porous SiO_2-SiC based ceramics annealed in argon atmosphere showed the decrease in compressive strength from 24.8 – 14.1 MPa when initial nano-SiC content increased from 0 to 35 wt%. The compressive strength of air annealed porous SiC ceramics decreased from 10.6 – 4.0 MPa as initial nano-SiC content increases from 0 to 35 wt%.

The decline in strength is directly linked to increased porosity, reduced cross-sectional load-bearing area, and more defects or pore stress concentrators. In air-annealed samples, the oxidation-driven creation of weak SiO_2 phases and larger pores exacerbates mechanical degradation. The argon-annealed samples maintain relatively higher strength because of limited oxidation and more coherent phase interfaces.

In a log–porosity plot, one might expect a linear or near-linear relation consistent with empirical strength–porosity models. The stronger performance under argon following the same porosity range suggests that microstructural control (e.g. pore geometry, neck thickness) is better preserved in inert atmosphere.

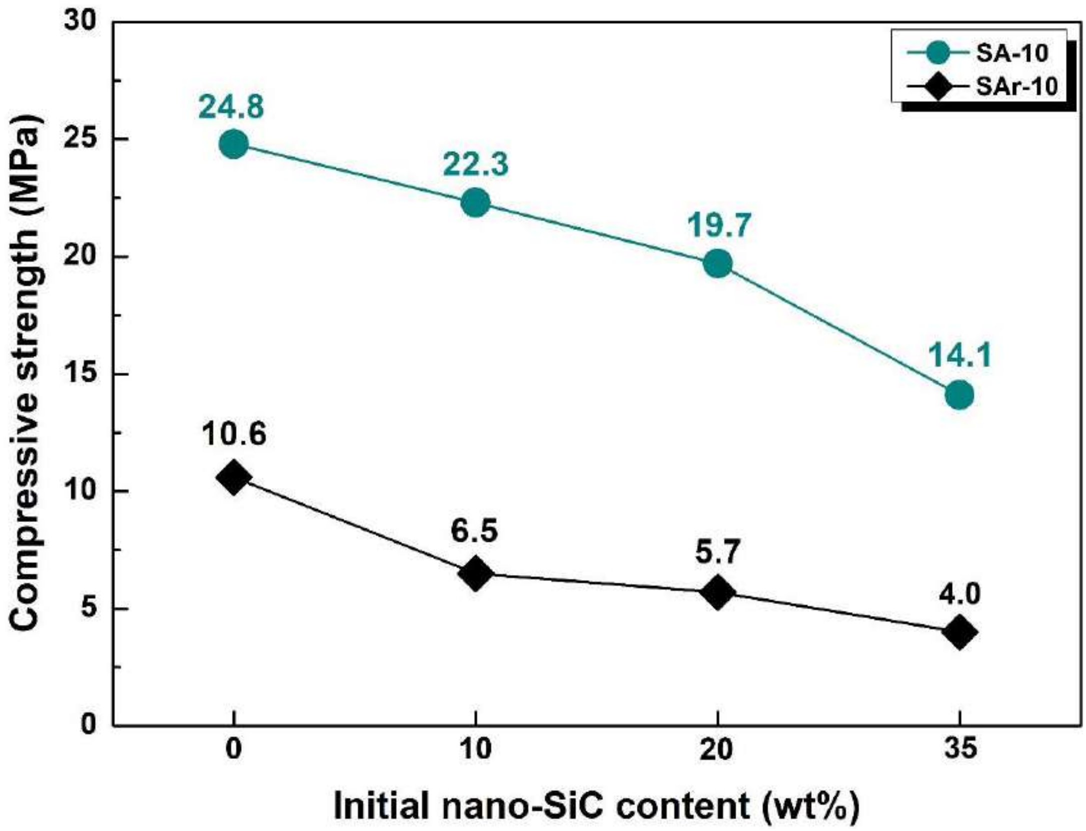

Figure 3 – Compressive strength of the porous SiO_2-SiC based ceramics as a function of initial nano-SiC content.

5 CONCLUSIONS

The effects of annealing atmosphere (argon vs. air) at 1000 °C for 1 h on porous SiO_2–SiC ceramics with varying nano-SiC contents were systematically studied. Key findings:

(1) Porosity increases with SiC content in both atmospheres; the increase is more substantial in air due to oxidation-induced pore formation.

(2) Thermal conductivity decreases correspondingly, with the lowest value of 0.045 W m^{-1} K^{-1} achieved in the air series.

(3) Compressive strength diminishes with SiC addition, with argon-annealed samples retaining higher strength compared to air-annealed ones.

These results illustrate that annealing atmosphere is a crucial parameter in balancing thermal insulation performance and mechanical reliability in porous SiO_2–SiC ceramics. Annealing in air yields extremely low thermal conductivity but at the cost of mechanical strength, while argon annealing provides a more favorable balance for structural applications.

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