UDC 691.32
IRSTI 67.09.33
RESEARCH ARTICLE

INVESTIGATION OF PHYSICO-CHEMICAL PROPERTIES CHANKANAI DEPOSIT ZEOLITES FOR ENHANCED MODIFIED CONCRETE PRODUCTION

A.K. Tolegenova[1], K. Akmalaiuly[1], A. Zhagifarov[1,*], A. Yespayeva[1], Z. Altayeva[2], A. Alikhan[1], Y. Merkibayev[1], Sh. Kultayeva[2], I.D. Teshev[1]

[1]Satbayev University, 050013, Almaty, Kazakhstan
[2]International Educational Corporation, 050043, Almaty, Kazakhstan

Abstract. *This study examines the physico-chemical properties of the Chankanai deposit zeolite and its potential as an additive in the production of modified concrete. The focus is on the investigation of the structural characteristics of zeolite, its chemical composition, and its modifying ability. Zeolites are aluminosilicate minerals with high adsorption capacity, and their use in building materials has the potential to enhance the strength, durability, and environmental friendliness of final products. X-ray diffraction (XRD) and scanning electron microscopy (SEM) methods were applied to analyze the structure and morphology of zeolites. The XRD methods allowed for the determination of the crystal structure and phase composition of zeolite samples, revealing the presence of dominant mineral phases and their spatial arrangement. Using SEM, the microstructure and morphological features of zeolite particles were investigated, enabling an assessment of their porosity and distribution within the material. As a result of the experiments, it has been found that zeolites exhibit a high sorption capacity, well-developed porous structure, thermal stability, and resistance to chemical substances, making them promising raw materials for manufacturing cement composites, concrete, and other building materials. Additionally, the potential of enhancing the performance of these materials through the use of zeolites as well as the environmental and economic benefits associated with them have been discussed.*

Keywords: *zeolite, Chankanai deposit, modified concretes, adsorption capacity, durability, environmental friendliness, physical properties.*

***Corresponding author**
Adlet Zhagifarov, e-mail: a.zhagifarov@satbayev.university

https://doi.org/10.51488/1680-080X/2024.4-13
Received 22 October 2024; Revised 12 November 2024; Accepted 21 November 2024

ӘОЖ 691.32
FТАМР 67.09.33
ҒЫЛЫМИ МАҚАЛА

ЖАҚСАРТЫЛҒАН МОДИФИКАЦИЯЛАНҒАН БЕТОН ӨНДІРУ ҮШІН ЧАНКАНАЙ КЕН ОРНЫНЫҢ ЦЕОЛИТТЕРІНІҢ ФИЗИКАӨХИМИЯЛЫҚ ҚАСИЕТТЕРІН ЗЕРТТЕУ

А.К. Толегенова[1], К. Ақмалайұлы[2], А. Жагифаров[1,*], А.С. Еспаева[1], З.Н. Алтаева[2], А. Алихан[1], Е. Меркибаев[1], Ш.М. Култаева[2], И.Д. Тешев[1]

[1]Сәтбаев Университеті, 050013, Алматы, Қазақстан
[2] Халықаралық білім беру корпорациясы, 050043, Алматы, Қазақстан

Аңдатпа. *Бұл зерттеу Чанканай кен орнының цеолитінің физика-химиялық қасиеттерін және оның модификацияланған бетондарды өндіруге арналған қоспа ретіндегі перспективаларын қарастырады. Цеолиттің құрылымдық ерекшеліктерін, оның химиялық құрамын және модификация қабілетін зерттеуге баса назар аударылады. Цеолиттер-жоғары адсорбциялық қабілеті бар алюминий силикаттары және оларды құрылыс материалдарында қолдану соңғы өнімнің беріктігін, беріктігін және тұрақтылығын арттыра алады. Цеолиттердің құрылымы мен морфологиясын талдау үшін рентгендік фазалық талдау (XRD) және сканерлеуші электронды микроскопия (SEM) әдістері қолданылды. Рентгендік фазалық әдіс цеолиттердің кристалдық құрылымы мен фазалық құрамын анықтауға, басым минералдардың болуын және олардың кеңістіктік ұйымдастырылуын анықтауға мүмкіндік берді. SEM көмегімен цеолит бөлшектерінің микроқұрылымы мен морфологиясы зерттелді, бұл олардың кеуектілігі мен материалдағы бөлшектердің таралуын бағалауға мүмкіндік берді. Эксперименттер нәтижесінде цеолиттердің жоғары сорбциялық қабілеті, дамыған кеуекті құрылымы, ыстыққа төзімділігі және химиялық реагенттердің әсеріне төзімділігі анықталды, бұл оларды цемент композиттерін, бетонды және басқа құрылыс материалдарын өндіруге перспективалы шикізат етеді. Сонымен қатар, цеолиттерді пайдалану арқылы құрылыс материалдарының өнімділігін жақсарту мүмкіндіктері, сондай-ақ олардың экологиялық және экономикалық артықшылықтары талқыланады.*

Түйін сөздер: *цеолит, Чанканай кен орны, өзгертілген бетондар, адсорбция қабілеті, беріктігі, тұрақтылығы, физикалық қасиеттері.*

***Автор-корреспондент**
Адлет Жагифаров, e-mail: a.zhagifarov@satbayev.university

https://doi.org/10.51488/1680-080X/2024.4-13
Алынды 22 қазан 2024; Қайта қаралды 12 қараша 2024; Қабылданды 21 қараша 2024

УДК 691.32
МРНТИ 67.09.33
НАУЧНАЯ СТАТЬЯ

ИССЛЕДОВАНИЕ ФИЗИКО-ХИМИЧЕСКИХ СВОЙСТВ ЦЕОЛИТОВ МЕСТОРОЖДЕНИЯ ЧАНКАНАЙ ДЛЯ ПРОИЗВОДСТВА УЛУЧШЕННОГО МОДИФИЦИРОВАННОГО БЕТОНА

А.К. Толегенова[1], К. Ақмалайұлы[2], А. Жагифаров[1,*], А.С. Еспаева[1], З.Н. Алтаева[2], А. Алихан[1], Е. Меркибаев[1], Ш.М. Култаева[2], И.Д. Тешев[1]

[1]Сатбаев Университет, 050013, Алматы, Казахстан
[2]Международная образовательная корпорация, 050028, Алматы, Казахстан

Аннотация. *В данном исследовании рассматриваются физико-химические свойства цеолита месторождения Чанканай и его перспективы в качестве добавки для производства модифицированных бетонов. Основное внимание уделено изучению структурных особенностей цеолита, его химического состава и способности к модификации. Цеолиты - это алюмосиликаты с высокой адсорбционной способностью, и их использование в строительных материалах может повысить прочность, долговечность и экологичность конечного продукта. Для анализа структуры и морфологии цеолитов были использованы методы рентгенофазового анализа (XRD) и сканирующей электронной микроскопии (SEM). Рентгенофазовый метод позволил определить кристаллическую структуру и фазовый состав цеолитов, выявив наличие доминирующих минералов и их пространственную организацию. С помощью SEM были изучены микроструктура и морфология частиц цеолита, что позволило оценить их пористость и распределение частиц в материале. В результате экспериментов было выявлено, что цеолиты обладают высокой сорбционной способностью, развитой пористой структурой, термостойкостью и стойкостью к воздействию химических реагентов, что делает их перспективным сырьем для изготовления цементных композитов, бетона и других строительных материалов. Кроме того, обсуждаются возможности улучшения эксплуатационных характеристик строительных материалов за счет использования цеолитов, а также их экологические и экономические преимущества.*

Ключевые слова: *цеолит, месторождение Чанканай, модифицированные бетоны, адсорбционная способность, долговечность, экологичность, физические свойства.*

***Автор-корреспондент**
Адлет Жагифаров, e-mail: a.zhagifarov@satbayev.university

https://doi.org/10.51488/1680-080X/2024.4-13
Поступило 22 октября 2024; Пересмотрено 12 ноября 2024.; Принято 21 ноября 2024

ACKNOWLEDGEMENTS/SOURCE OF FUNDING

This research is funded by the Committee of Science of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. AP22685758 – “Zeolite-containing modified concrete for monolithic construction”).

CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

АЛҒЫС / ҚАРЖЫЛАНДЫРУ КӨЗІ

Бұл зерттеуді Қазақстан Республикасы Ғылым және жоғары білім министрлігінің Ғылым комитеті қаржыландырады (№AP22685758 «Монолитті құрылысқа арналған құрамында цеолиті бар модификацияланған бетон" гранты).

МҮДДЕЛЕР ҚАҚТЫҒЫСЫ

Авторлар мүдделер қақтығысы жоқ екенін растайды.

БЛАГОДАРНОСТИ/ИСТОЧНИК ФИНАНСИРОВАНИЯ

Данное исследование финансируется Комитетом науки Министерства науки и высшего образования Республики Казахстан (грант № AP22685758 «Цеолитсодержащий модифицированный бетон для монолитного строительства»).

КОНФЛИКТ ИНТЕРЕСОВ

Авторы подтверждают, что конфликта интересов нет.

1 INTRODUCTION

In recent years, the construction industry has been increasing interest in the use of natural zeolites to create modified concretes with improved physical and mechanical properties. Zeolites are natural aluminosilicates with a microporous structure, which gives them unique sorption and catalytic properties. Due to these qualities, zeolites can significantly improve the properties of concrete, such as strength, durability and resistance to aggressive environments.

The Chankanai deposit, located in the Almaty region of Kazakhstan, is one of the promising sources of natural zeolite. The study of the physico-mechanical characteristics of zeolite from this deposit, as well as its potential as an additive for the modification of concrete mixtures, is an urgent task for the construction science and industry of Kazakhstan. The introduction of zeolite into the composition of concrete can not only improve its performance properties but also reduce the environmental impact by reducing the need for traditional cement components.

The purpose of this study is to study the properties of the zeolite of the Chankanai deposit and assess its effect on the characteristics of modified concrete, which will allow the development of more stable and efficient building materials.

2 LITERATURE REVIEW

Concrete is one of the most common building materials for civil and military use due to its high mechanical stability and durability. However, its production has a significant impact on the environment since the production process of Portland cement, the main hydraulic component of concrete is accompanied by CO_2 emissions amounting to approximately 6% of global emissions of this gas (**Hefni et al., 2018**). Over time, concrete structures are exposed to various factors of destruction, such as shrinkage, freezing, and exposure to chlorides and sulfates, which reduce their durability. It is also important to take into account the costs of maintenance, protection, repair and restoration of existing concrete structures. Several practical solutions have been proposed to solve these problems. The first is to improve concrete's mechanical structure and durability during the production process. The second is to reduce the consumption of Portland cement in the production process. These two approaches can be implemented by optimizing the packing density of particles in concrete (**Kurda et al., 2019**) and partially replacing Portland cement with natural pozzolans and/or by-products of industrial production of pozzolan materials, such as crushed granular blast furnace slag (GGBFS), fly ash, or silica fume **(Eskandari et al., 2015; Markiv et al., 2016; Nuruddin et al., 2014; Shariq et al., 2016)**.

Zeolites are hydrated aluminosilicates that are mainly composed of four-, five- and six-membered rings formed by silicon-oxygen tetrahedra. Some of the silicon atoms in these rings can be replaced by aluminum (**Zhdanov & Yegorova, 1968; Rabo, 1980; Zhdanov et al., 1981; Pekov et al., 2004**). In the intercrystalline space, there is a system of interconnected channels that contain micro-cavities. These cavities are filled with exchange cations and water molecules. Zeolite is a nanoscale material that forms an ordered structure when molecules and ions are embedded into its framework. This creates a unique material with specific properties (**Kryuchin et al., 2010**). Due to their strictly defined pore sizes and intercrystalline cavities, both natural and synthetic zeolites are excellent sorbents - molecular "sieves" (**Breck, 1976**) capable of selectively absorbing and releasing molecules of various substances. After dehydration, zeolites can have a porosity of up to 50% or more, and their crystal structure is formed by fragments of tetrahedral anions $[SiO4]^{4-}$ and $[AlO4]^{5-}$ combined into a three-dimensional framework with cavities and channels of 0.2-1.5 nm scale.

Natural zeolite is becoming an increasingly popular component in concrete production due to its pozzolanic properties and positive effect on environmental friendliness. The addition of zeolite as a supplementary cementing material reduces CO_2 emissions by decreasing the amount of Portland cement required while improving the performance of concrete. However, research shows that the impact of zeolite on mechanical properties and durability depends on several factors, including the composition of the zeolite, level of replacement, and testing conditions.

The incorporation of natural zeolite into concrete has led to a significant improvement in its mechanical properties. Uzal and Turanli (**Uzal & Turanlı, 2012**) studied cements containing a high concentration of zeolite and found that the strength of the cement stone increased due to the formation of additional C-S-H phases. This is because of the pozzolanic reaction, in which zeolite reacts with calcium hydroxide to produce additional hydrated phases, reducing porosity and increasing the density of the material. However, when a large proportion of cement is replaced with zeolite (more than 30%), the strength gain may be slowed in the early stages. This can be a disadvantage for applications that require rapid strength development.

Pezeshkian et al. (**Pezeshkian et al., 2020**) examined the impact of natural zeolite on ultra-high-performance concrete (UHPC) and observed a decrease in autogenous shrinkage. This decrease helps lower the likelihood of cracking by enhancing water retention and reducing the rate of heat release during hydration. Nevertheless, the delayed hydration process could be problematic for applications where quick strength development is essential. Similarly, Ranjbar et al. (**Ranjbar et al., 2013**) reported that the addition of zeolite improved the rheological properties of self-compacting concrete by minimizing water bleeding and increasing water retention, resulting in a more homogeneous mixture. However, they also noted that when a high percentage of cement was replaced with zeolite, the initial strength of the concrete decreased due to the lower reactivity of the zeolite. Several researchers have investigated the durability of concrete containing zeolite. While zeolite can improve the properties of concrete, it is important to consider each project's specific conditions and requirements when deciding whether to use it.

Natural zeolite has been shown to have a positive effect on the durability of concrete, enhancing its resistance to various aggressive factors. Studies by Cryptavicius et al. (**Kriptavičius et al., 2023**) and Singgu et al. (**Sinngu et al., 2024**) have demonstrated that the addition of zeolite to concrete can improve its resistance to chloride and sulfate attack. Zeolite reacts with calcium hydroxide in the concrete to form additional calcium silicate hydrate (C-S-H) gels, which help to seal the microstructure of the concrete and reduce its permeability. This, in turn, reduces the risk of chloride and sulfate penetration, leading to increased durability.

The effectiveness of zeolite in improving concrete durability is dependent on several factors, including its chemical composition, physical characteristics such as particle size, and mineralogical composition. It is important to carefully select and use zeolite that is suitable for the specific application in order to maximize its benefits. Despite the obvious advantages of using natural zeolite in concrete, there are several challenges associated with its use. One of the main problems lies in the variability of zeolite composition, which can affect its pozzolanic activity and, consequently, the properties of the concrete. Uzal and Turanli (**Uzal & Turanlı, 2012**) noted that excessive amounts of zeolite can slow down strength gain due to its slow reaction in the early stages of hydration, limiting its use in applications requiring rapid strength development.

Several number of researchers emphasized the importance of optimizing zeolite replacement levels in concrete. Improper composition selection can lead to decreased strength and reduced durability. To achieve optimal results, it is crucial to consider the specific application requirements and characteristics of the selected zeolite.

In conclusion, while the use of zeolite has many benefits, it also presents challenges that must be addressed. By carefully considering these factors, engineers can optimize concrete formulations and ensure successful outcomes in various applications. Natural zeolite is a promising component for concrete modification that offers several advantages, including improved mechanical properties and increased durability. Its use can reduce the amount of Portland cement used, leading to a reduction in CO_2 emissions and lower costs. However, to effectively utilize zeolite, it is important to consider its chemical composition, level of replacement, and operating conditions.

3 MATERIALS AND METHODS

Zeolite was received from Chankanai deposit (Almaty region, Kazakhstan, LTD Taza Su). The zeolite was grinned, ground, and sieved to 200 mesh (or 105 nμ) in size. The certified chemical composition of natural zeolite is provided in **Table 1.** To determine the elemental composition, the sample was subjected to X-ray spectral analysis at the Superprob 733 device (Japan), and to determine the mineral composition to X-ray phase analysis at the DRON - 3 device (USSR), and a Scanning electron microscope JEOL (Japan) was used to determine the microstructure.

Table 1
Chemical composition of the studied zeolite, mass % (author's material).

Oxides	ω, %	Oxides	ω, %
SiO_2	67.38	Na_2O	1.08
Al_2O_3	16.67	K_2O	1.57
FeO	3.62	TiO_2	0.6
CaO	6.3	MnO	0.17
MgO	2.60	Total	100

4 RESULTS AND DISCUSSION

It is known that zeolites are nanoporous crystalline aluminosilicates containing water molecules and exchangeable cations such as K+, Na+, Ca^2+ and Mg^2+, which neutralize excess negative charges arising from the isomorphic substitution of Si^{4+} with Al^{3+}. The primary structural unit of zeolites is conventionally taken to be the TO4 tetrahedron, where T is a silicon or aluminum atom Tetrahedra, connecting with each other, form cuboctahedra (sodalite cells), from which the elementary cells of zeolite are built from three-, four-, five- or six-membered rings that make up its crystalline framework (**Nisbet, 1997; Sweeck et al. 1990**). The cuboctahedra are connected to each other by channels, the accessibility of which is determined by the free cross-section of the entrance holes (windows) formed by rings of interconnected tetrahedra.

The sorption properties of zeolite rocks are significantly influenced by both the mineral composition and the structural characteristics of the mineral (**Figure 1**). Zeolites possess a microporous structure, and zeolite-containing rock is a mixture of zeolite and other impurity minerals. As a result, meso- and macropores are formed between zeolite particles and the surrounding rock matrix, which aids in the interdiffusion of exchangeable ions within the sorbent–sorbate system (**Mamytbekov et al., 2024**). Impurity minerals, such as layered aluminosilicates like montmorillonite and occasionally halloysite, may also be present.

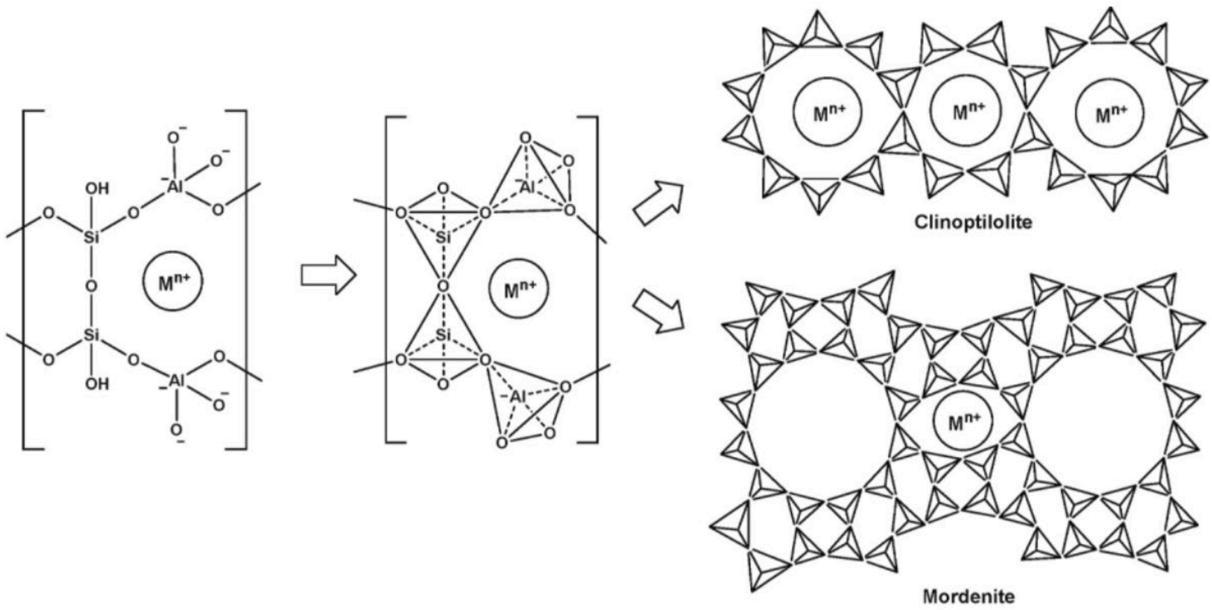

Figure 1 – General zeolite structure (Nisbet, 1997; Sweeck et al. 1990).

4.1 SEM ANALYSIS

The microstructural characteristics of the zeolite samples were evaluated using Scanning Electron Microscopy (SEM), which provided valuable insights into the morphology, particle size distribution, and surface texture, as demonstrated on Figure 2.

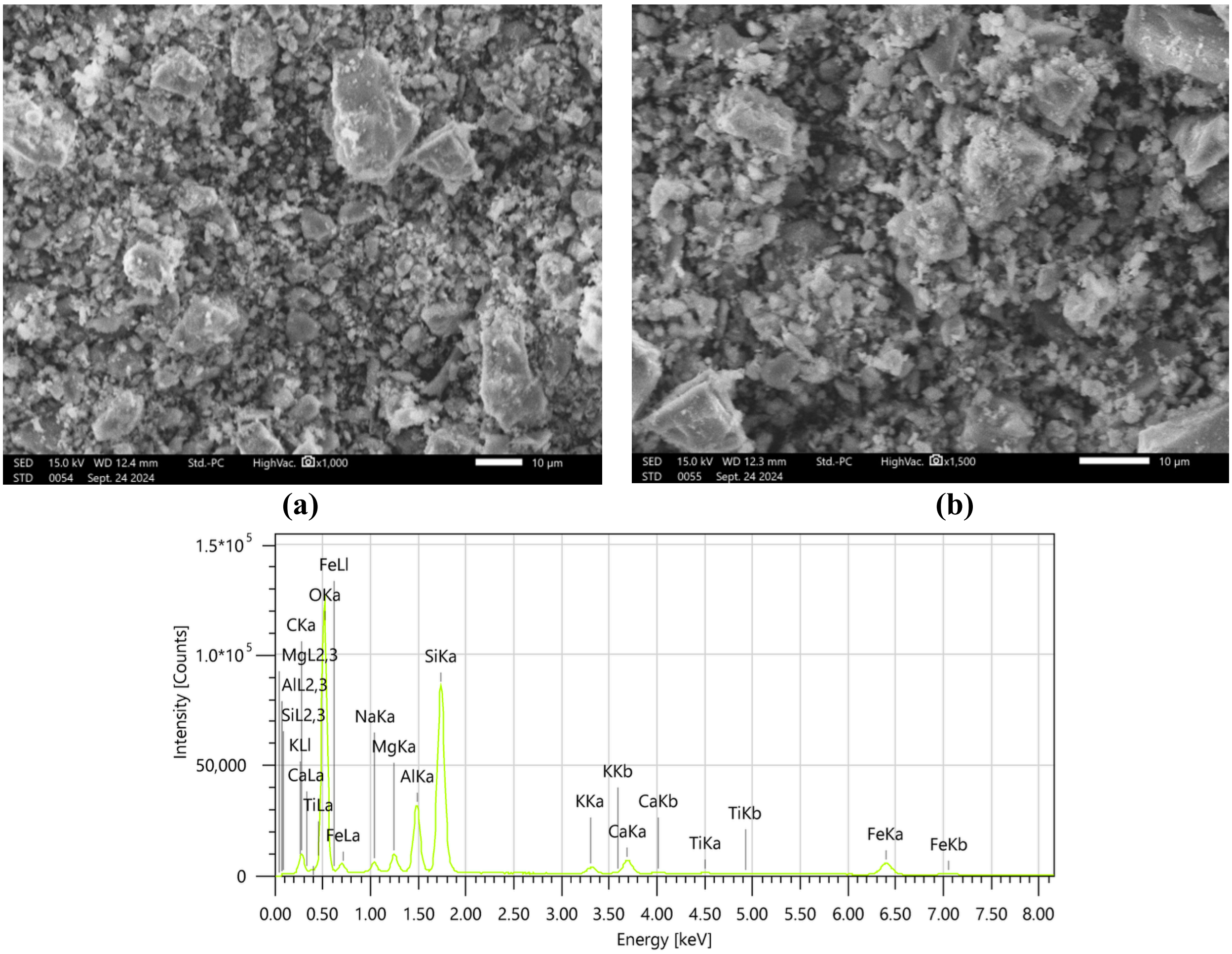

Figure 2 – SEM images of Zeolite (a) (b) and elemental analysis (c) (author's material).

The images show irregularly shaped particles, which is typical for natural zeolites. The particles have a granular texture and vary in size. At a magnification of 1500, agglomerations of small crystalline particles can be distinguished, which form larger structures. Individual larger crystals are also visible, probably with well-defined faces, which may indicate the presence of clinoptilolite or other zeolite phases. The scale (10 µm) shows that the particles range from sub microns to several microns.

Fine particles can contribute to an increase in the total surface area, which has a positive effect on the adsorption properties of zeolite. The visible crystals have a size of about 1-5 microns, which is typical for natural zeolites used as adsorbents. The surface of the particles looks rough and porous, which is an important characteristic of zeolites, since the porous structure provides a high specific surface area. The presence of pores and the heterogeneous structure of the surface can be a confirmation of the high adsorption capacity of zeolite, which makes it suitable for use in water purification processes or as a catalyst. The particles tend to agglomerate, which is typical for fine crystalline minerals. Agglomeration can affect the effectiveness of zeolite application in industrial processes, as it reduces the available surface.

SEM images of natural zeolite show that the sample consists of irregularly shaped particles ranging in size from a submicron to several microns, having a highly developed porous surface. Such structural features confirm the potential of zeolite for use in adsorption and catalytic processes.

4.2 XRD ANALYSIS

During the study, X-ray diffraction analysis (XRD) of a sample of natural zeolite was performed to determine its mineral composition (**Figure 3**). Characteristic peaks are observed on the resulting diffractogram, which make it possible to identify the main and secondary phases in the sample. Based on a comparison of the values of interplane distances with the database of standard diffraction maps (PDF), it is assumed that clinoptilolite dominates in the sample, which is confirmed by the presence of peaks at 3.98 Å and 3.34 Å. The presence of mordenite is also likely (peaks at 9.02 Å and 6.73 Å), which is typical for natural zeolites, often mixtures of several phases.

Natural zeolites are rarely found in their pure form, and peaks are also observed on the diffractogram, which may correspond to impurities. For example, the peak at 3.34 Å may be associated with quartz, since this value is typical for this mineral.

XRD analysis showed that the studied sample of natural zeolite contains clinoptilolite and probably mordenite, as well as impurities of other mineral phases such as quartz. These results are important for understanding the properties of zeolite and can be used to evaluate its adsorption and catalytic characteristics. Results of semi-quantitative X-ray phase analysis of crystalline phases: Clinoptilolite – (Na, K, Ca)2.5Al_3(Al,Si)2$Si_{13}O_{36}$•12H_2O 84.5%; quartz – SiO_2 -10.2%; Albite (Feldspar) – Na($AlSi_3O_8$) – 5.3%.

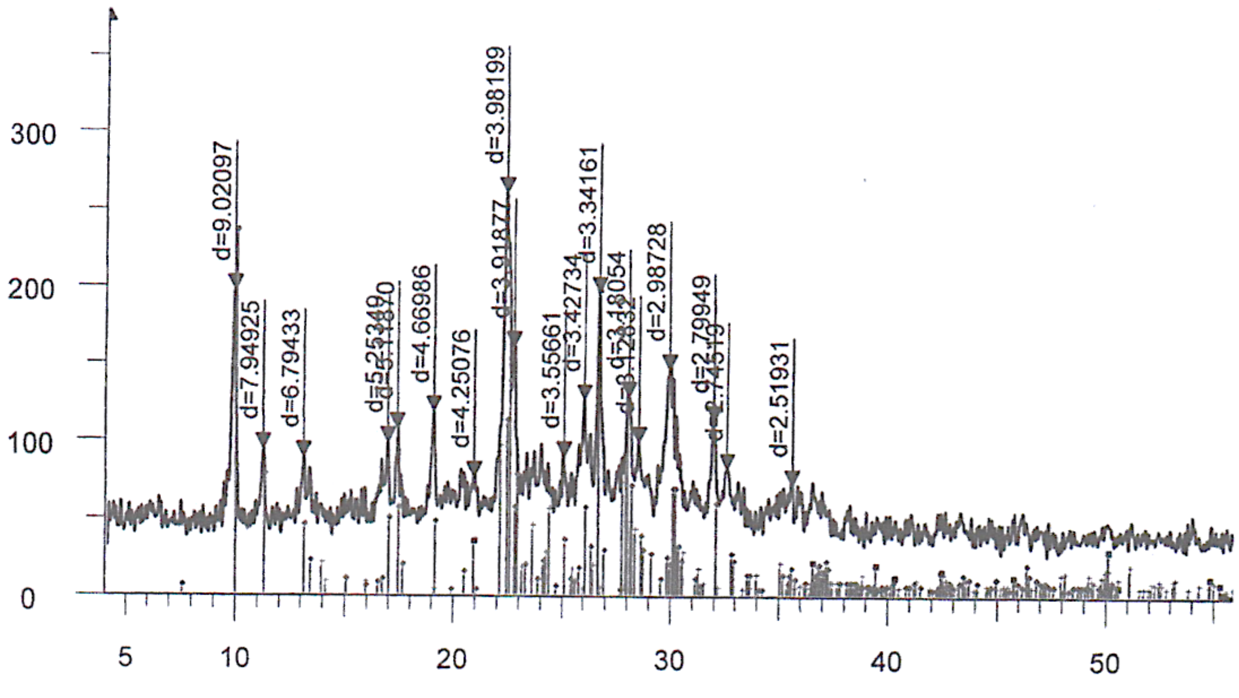

Figure 3 – XRD spectra of Zeolite (author's material).

5 CONCLUSIONS

During the study, the structural, chemical and morphological characteristics of natural zeolite from the Chankanai deposit (Almaty region, Kazakhstan) were studied. The conducted analyses, including SEM, X-ray diffraction and X-ray spectral analysis, allowed us to determine the basic mineral composition and structural features of the sample. The results showed that the main mineral is clinoptilolite with possible admixtures of mordenite and quartz, which is typical for natural zeolites, often containing mixtures of several phases.

SEM analysis revealed that zeolite particles have an irregular shape and granular texture, and their size varies from submicron to several microns. The surface morphology, represented by small crystalline particles with a coarse, porous structure, confirms the high sorption capacity of zeolite. These structural features make this material promising for use in adsorption and catalytic processes, especially in water purification and industrial catalysis.

XRD analysis confirmed the presence of clinoptilolite as the main phase, while peaks corresponding to quartz and possibly mordenite were found. This indicates a complex mineral composition of the sample under study.

Thus, the study showed that zeolite from the Changkanai deposit has a high potential for practical applications, such as water purification, due to its structural features, high specific surface area, and excellent adsorption characteristics. In the future, research could evaluate the catalytic properties of zeolite, study its durability, and develop optimization methods for various industrial applications.

REFERENCES

1. **Eskandari, H., Vaghefi, M., & Kowsari, K.** (2015). Investigation of Mechanical and Durability Properties of Concrete Influenced by Hybrid Nano Silica and Micro Zeolite. Procedia Materials Science, 11, 594–599. https://doi.org/10.1016/j.mspro.2015.11.084
2. **Hefni, Y., Zaher, Y. A. E., & Wahab, M. A.** (2018). Influence of activation of fly ash on the mechanical properties of concrete. Construction and Building Materials, 172, 728–734. https://doi.org/10.1016/j.conbuildmat.2018.04.021
3. **Kriptavičius, D., Girskas, G., Ivanauskas, E., & Korjakins, A.** (2023). Complex Effect of Portland Cement Modified with Natural Zeolite and Ground Glass Mixture on Durability Properties of Concrete. Buildings, 13(10), 2576. https://doi.org/10.3390/buildings13102576
4. **Kurda, R., De Brito, J., & Silvestre, J. D.** (2019). Water absorption and electrical resistivity of concrete with recycled concrete aggregates and fly ash. Cement and Concrete Composites, 95, 169–182. https://doi.org/10.1016/j.cemconcomp.2018.10.004
5. **Markiv, T., Sobol, K., Franus, M., & Franus, W.** (2016). Mechanical and durability properties of concretes incorporating natural zeolite. Archives of Civil and Mechanical Engineering, 16(4), 554–562. https://doi.org/10.1016/j.acme.2016.03.013
6. **Nuruddin, M. F., Chang, K. Y., & Mohd Azmee, N. (**2014). Workability and compressive strength of ductile self compacting concrete (DSCC) with various cement replacement materials. Construction and Building Materials, 55, 153–157. https://doi.org/10.1016/j.conbuildmat.2013.12.094
7. **Zhdanov, S. P., & Yegorova, E. N.** (1968). Chemistry of Zeolites [Himiya ceolitov]. Leningrad: Nauka. (In Rus.).
8. **Rabo, J.** (1980). Chemistry of Zeolites and Catalysis on Zeolites [Himiya ceolitov i kataliz na ceolitah]. Volume 1 (Trans. from English). Moscow: Mir. (In Rus.).
9. **Zhdanov, S. P., Khvoshchev, S. S., & Feoktistova, N. N.** (1981). Synthetic Zeolites [Sinteticheskie ceolity]. Moscow: Khimiya. (In Rus.).

10. **Pekov, I. V., Turchkova, A. G., Lovskaya, E. V., & Chukanov, N. V.** (2004). Zeolites of Alkaline Massifs [Ceolity shchelochnyh massivov]. Moscow: Ekost. (In Rus.).
11. **Kryuchin, A. A., Kossko, I. A., Firstov, S. A., & Khizhun, O. Y.** (2010). On the synergistic phenomenon of the nanostructured composite dye-zeolite. Registration, Storage and Data Processing, 12(2), 52–56. (In Rus.).
12. **Breck, D.** (1976). Zeolite Molecular Sieves [Molekulyarnye sita iz ceolita] (Trans. from English). Moscow: Mir. (In Rus.).
13. **Pezeshkian, M., Delnavaz, A., & Delnavaz, M.** (2020). Effect of Natural Zeolite on Mechanical Properties and Autogenous Shrinkage of Ultrahigh-Performance Concrete. Journal of Materials in Civil Engineering, 32(5), 04020093. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002968
14. **Ranjbar, M. M., Madandoust, R., Mousavi, S. Y., & Yosefi, S.** (2013). Effects of natural zeolite on the fresh and hardened properties of self-compacted concrete. Construction and Building Materials, 47, 806–813. https://doi.org/10.1016/j.conbuildmat.2013.05.097
15. **Shariq, M., Prasad, J., & Abbas, H.** (2016). Creep and drying shrinkage of concrete containing GGBFS. Cement and Concrete Composites, 68, 35–45. https://doi.org/10.1016/j.cemconcomp.2016.02.004
16. **Sinngu, F., Ekolu, S. O., Modisane, L., & Solomon, F. H.** (2024). Effects of natural zeolite on mechanical properties and durability indexes of concrete. Proceedings of the Institution of Civil Engineers - Construction Materials, 177(5), 321–333. https://doi.org/10.1680/jcoma.23.00079
17. **Uzal, B., & Turanlı, L.** (2012). Blended cements containing high volume of natural zeolites: Properties, hydration and paste microstructure. Cement and Concrete Composites, 34(1), 101–109. https://doi.org/10.1016/j.cemconcomp.2011.08.009
18. **Nisbet, A., Konoplev, A. V., Shaw, G., Lembrechts, J. F., Merckx, R., Smolders, E., Vandecasteele, C. M., Lönsjö, H., Carini, F., & Burton, O.** (1993). Application of fertilisers and ameliorants to reduce soil to plant transfer of radiocaesium and radiostrontium in the medium to long term - a summary. Science of the Total Environment, The, 137(1-3), 173-182. https://doi.org/10.1016/0048-9697(93)90386-K
19. **Desmet, G., & Nassimbeni, P. Belli, M.** (1990). Transfer of radionuclides in natural and semi-natural environments. (Ed.), (p.707). United Kingdom: Elsevier Applied Science.