UDC 691:504.064:66.074.3
IRSTI 67.09.33; 87.15.09
RESEARCH ARTICLE

# INTEGRATION OF LIMESTONE WASTE PROCESSING AND CCU TECHNOLOGIES IN THE PRODUCTION BUILDING MATERIALS

**I.A. Rustemov**[1], **D.E. Yelemes**[1,*], **K.A. Nauruzbayev**[1], **G.H. Kereybayeva**[1], **M.R. Karipova**[1], **A.K. Nurakhova**[1], **M.U. Khodjabekov**[2]

[1]L.B. Goncharov Kazakh Automobile and Road Institute, 050061, Almaty, Kazakhstan
[2]Mirzo Ulugbek Samarkand State University of Architecture and Construction, 140147, Samarkand, Uzbekistan

**Abstract.** *Carbonate raw material processing generates significant limestone screenings and* $CO_2$ *emissions from the chemical decarbonization reaction (*$CaCO_3 \rightarrow CaO + CO_2$*). Fragmented environmental measures fail to systematically reduce the overall environmental burden. This study develops an integrated approach to managing mineral and carbon flows. The methodology includes analysis of scientific publications, examination of technological schemes, balance modeling of material and carbon flows, and conceptual assessment of integrating Carbon Capture and Utilization (CCU) technologies into wet flue gas cleaning systems. Implementation of the integrated scheme enables the involvement of 85–95% of limestone screenings in secondary economic circulation. Process decarbonization calculations show* $CO_2$ *emissions reach approximately 0.418 t per ton of processed raw material (95%* $CaCO_3$ *content). CCU implementation with 60% capture efficiency reduces total* $CO_2$ *emissions by 30–40%. Comparative analysis reveals a synergistic environmental effect through comprehensive management of solid, particulate, and gaseous flows. Landfill volumes decrease by 6–10 times compared to fragmented management. The proposed concept aligns with circular economy principles and serves as a methodological basis for modernizing carbonate processing enterprises.*

**Keywords:** *limestone screenings,* $CO_2$ *emissions, decarbonization, carbon capture and utilization (CCU); wet gas cleaning; circular economy; integrated approach*

***Corresponding author**
**Darkhanrayis Yelemes**, e-mail: techmashkz@gmail.com

**https://doi.org/10.51488/1680-080X/2026.1-18**
Received 25 February 2026; Revised 14 March 2026; Accepted 28 March 2026

ӘОЖ 691:504.064:66.074.3
ҒТАМР 67.09.33; 87.15.09
ҒЫЛЫМИ МАҚАЛА

# ИЗВЕСТНЯК ҚАЛДЫҚТАРЫН ҚАЙТА ӨҢДЕУ МЕН CCU ТЕХНОЛОГИЯЛАРЫН ҚҰРЫЛЫС МАТЕРИАЛДАРЫН ӨНДІРУГЕ ИНТЕГРАЦИЯЛАУ

**И.А. Рустемов**[1], **Д.Е. Елемес**[1,*], **К.А. Наурузбаев**[1], **Г.Х. Керейбаева**[1],
**М.Р. Карипова**[1], **А.К. Нурахова**[1], **М.У. Ходжабеков**[2]

[1]Л.Б. Гончаров атындағы Қазақ автомобиль-жол институты,
050061, Алматы, Қазақстан
[2]Мирзо Ұлықбек атындағы Самарқанд сәулет-құрылыс университеті,
140147, Самарқанд, Өзбекстан

---

**Аңдатпа.** *Карбонатты шикізатты қайта өңдеу үдерісі майда дисперсті известняк фракцияларының (отсевтердің) едәуір көлемде түзілуімен, сондай-ақ химиялық декарбонизация реакциясына ($CaCO_3 \rightarrow CaO + CO_2$) байланысты көмірқышқыл газының бөлінуімен қатар жүреді. Жекелеген табиғатты қорғау шешімдерін үзік-үзік енгізу жиынтық экологиялық жүктемені жүйелі түрде төмендетуді қамтамасыз етпейді. Зерттеу минералдық және көміртектік ағындарды басқарудың интеграцияланған тәсілін әзірлейді. Әдіснамалық негізге ғылыми жарияланымдарды талдау, технологиялық сұлбаларды зерделеу, материалдық және көміртектік ағындардың баланстық модельденуі, сондай-ақ шығатын газдарды ылғалды тазалау кезінде $CO_2$-ні ұстау және пайдалану технологияларын (CCU) интеграциялау әлеуетін тұжырымдамалық бағалау кіреді. Интеграцияланған сұлбаны енгізу отсевтердің 85–95%-ына дейінін екінші реттік шаруашылық айналымға тартуға мүмкіндік береді. Процесс декарбонизациясын есептеу $CO_2$ шығарындылары өңделген шикізаттың әр тоннасына шамамен 0,418 т жететінін көрсетеді ($CaCO_3$ құрамдылығы 95%). 60% ұстау тиімділігімен CCU енгізу жалпы $CO_2$ шығарындыларын 30–40%-ға азайтады. Салыстырмалы талдау қатты, шаңтәрізді және газтәрізді өнім ағындарын кешенді басқару жағдайында синергетикалық экологиялық әсердің туындайтынын дәлелдейді. Фрагментарлық басқарумен салыстырғанда полигон көлемдері 6–10 есеге азаяды. Ұсынылған тұжырымдама циркулярлық экономика қағидаттарына сәйкес келеді және карбонатты материалдарды қайта өңдеу кәсіпорындарын жаңғыртудың әдіснамалық негізі бола алады.*

**Түйін сөздер:** *известняк қалдықтары, $CO_2$ қалдықтары, декарбонизация, CCU, газдарды ылғалды тазалау, циркулярлық экономика, интеграцияланған тәсіл*

---

***Автор-корреспондент**
**Дархanрайыс Елемес**, e-mail: techmashkz@gmail.com

**https://doi.org/10.51488/1680-080X/2026.1-18**
Алынды 25 ақпан 2026; Қайта қаралды 14 наурыз 2026; Қабылданды 28 наурыз 2026

УДК 691:504.064:66.074.3
МРНТИ 67.09.33; 87.15.09
НАУЧНАЯ СТАТЬЯ

# ИНТЕГРАЦИЯ ПЕРЕРАБОТКИ ИЗВЕСТНЯКОВЫХ ОТХОДОВ И ТЕХНОЛОГИЙ CCU В ПРОИЗВОДСТВЕ СТРОИТЕЛЬНЫХ МАТЕРИАЛОВ

**И.А. Рустемов[1], Д.Е. Елемес[1,*], К.А. Наурузбаев[1], Г.Х. Керейбаева[1], М.Р. Карипова[1], А.К. Нурахова[1], М.У. Ходжабеков[2]**

[1]Казахский автомобильно-дорожный институт им. Л.Б. Гончарова,
050061, Алматы, Казахстан
[2]Самаркандский архитектурно-строительный университет им. Мирзо Улугбека,
140147, Самарканд, Узбекистан

---

**Аннотация.** *Переработка карбонатного сырья сопровождается образованием значительных объёмов мелкодисперсных известняковых фракций (отсевов) и формированием выбросов диоксида углерода, связанных с химической реакцией декарбонизации ($CaCO_3 \rightarrow CaO + CO_2$). Фрагментарное внедрение отдельных природоохранных решений не обеспечивает системного снижения совокупной экологической нагрузки. Исследование разрабатывает интегрированный подход к управлению минеральными и углеродными потоками. Методологическую основу составляют анализ научных публикаций, изучение технологических схем, балансовое моделирование материальных и углеродных потоков, а также концептуальная оценка потенциала интеграции технологий улавливания и использования $CO_2$ (CCU) при мокрой очистке отходящих газов. Внедрение интегрированной схемы позволяет вовлекать до 85–95% отсевов во вторичный хозяйственный оборот. Расчеты процессной декарбонизации показывают, что выбросы $CO_2$ достигают приблизительно 0,418 т на тонну переработанного сырья (при содержании $CaCO_3$ 95%). Внедрение CCU с эффективностью улавливания 60% снижает общие выбросы $CO_2$ на 30–40%. Сравнительный анализ демонстрирует выраженный синергетический экологический эффект при комплексном управлении потоками твёрдых, пылевидных и газообразных продуктов. Объемы складирования отходов снижаются в 6–10 раз по сравнению с фрагментарным управлением. Предложенная концепция соответствует принципам циркулярной экономики и может служить методологической основой для модернизации предприятий переработки карбонатных материалов.*

**Ключевые слова:** *известняковые отсевы, выбросы $CO_2$, декарбонизация, CCU, мокрая очистка газов, циркулярная экономика, интегрированный подход*

---

***Автор-корреспондент**
**Дарханрайыс Елемес**, e-mail: techmashkz@gmail.com

**https://doi.org/10.51488/1680-080X/2026.1-18**
Поступила 25 февраля 2026; Пересмотрено 14 марта 2026; Принято 28 марта 2026

## ACKNOWLEDGEMENTS/SOURCE OF FUNDING

The study was conducted using private sources of funding.

## 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

Carbonate rocks, primarily limestone and dolomite, are among the most widely used mineral resources and serve as essential raw materials for the production of lime, cement, construction composites, mineral fillers, and various chemical products. Their global extraction and processing reach billions of tons annually, resulting in significant anthropogenic impacts on the environment throughout the entire production cycle-from mining and crushing to thermal treatment and handling of by-products.

A key feature of limestone processing is the thermal decarbonization of carbonate raw materials, which occurs at elevated temperatures and is accompanied by the release of carbon dioxide according to the reaction:

$$CaCO_3 \rightarrow CaO + CO_2 \qquad (1)$$

Unlike energy-related emissions associated with fuel combustion, process-related $CO_2$ emissions are inherently unavoidable, as they are determined by the chemical nature of lime production. This significantly limits the potential for reducing the carbon footprint solely through energy efficiency improvements or transition to low-carbon energy sources, making this industry a priority target for the development of specialized carbon management solutions **(Leung et al., 2014; IEA, 2018; Habert et al., 2020)**.

In addition to gaseous emissions, crushing, screening, and classification processes generate substantial volumes of limestone screenings, which may account for up to 30–35% of the processed raw material. These fractions are characterized by a high content of fine particles and a large specific surface area, leading to intensive dust formation during storage and transportation. The accumulation of screenings in dumps results in land occupation and creates persistent sources of secondary air pollution.

Thus, limestone processing generates interconnected mineral and carbon flows that are traditionally treated as separate environmental issues: on the one hand, the management of solid waste and dust emissions, and on the other hand, the reduction of $CO_2$ emissions. However, addressing these challenges separately limits the achievement of a comprehensive environmental effect and prevents the realization of potential synergies between them.

A review of scientific literature and industrial practices indicates that existing technological solutions are largely fragmented: screening utilization is considered independently from decarbonization, while $CO_2$ capture technologies are implemented without integration into mineral material flows. System-level approaches aimed at creating a unified mineral–carbon loop in lime production remain insufficiently developed **(Habert et al., 2020; Scrivener et al., 2018)**.

Research Gap: Despite extensive research on individual aspects of limestone processing, a critical gap remains in the systematic integration of solid waste management and carbon capture technologies. There is a lack of comprehensive models that consider limestone screenings processing and $CO_2$ capture as elements of a unified mineral–carbon loop.

Scientific Novelty: This study addresses this gap by developing a unified material–carbon flow model that quantifies the synergistic effect of combining screening utilization with wet gas cleaning and CCU technologies.

In the context of global climate strategies and the transition toward a circular economy, the development of integrated approaches for simultaneous management of solid and gaseous technogenic products becomes particularly relevant.

The aim of this study is to substantiate a concept of integrated $CO_2$ emission management and limestone screening utilization in lime production, incorporating wet gas cleaning and carbon capture and utilization (CCU) technologies.

The processing of carbonate raw materials is widely recognized as a significant source of anthropogenic environmental impact. Scientific studies primarily focus on two key aspects: $CO_2$ emissions associated with thermal decarbonization and the generation of dust emissions and solid mineral waste during crushing and calcination.

Analysis of studies on the carbon footprint of the industry shows that a substantial portion of $CO_2$ emissions originates from process-related decarbonization rather than fuel combustion. This distinguishes carbonate processing from most other energy-intensive industries and necessitates the development of specialized decarbonization strategies **(Leung et al., 2014; Hills et al., 2016; IEA, 2018; Habert et al., 2020)**.

Simultaneously, limestone crushing and classification processes generate fine screenings, which may constitute up to 30–35% of the processed material. Their accumulation leads to land use issues and the formation of secondary dust emission sources, deteriorating local air quality.

Thus, the environmental impact of carbonate processing is inherently dual in nature, involving both gaseous and solid technogenic flows.

A wide range of applications for limestone screenings has been proposed in the literature, including:

- use as mineral additives in mortars and concrete;
- application as fillers in composite materials;
- utilization in road construction **(Kazhetaev et al., 2025)**;
- incorporation into dry building mixtures;
- use as neutralizing and sorbent materials **(De Weerdt et al., 2011; Irassar et al., 2001; Chen et al., 2014)**.

Some studies also explore their application in animal feed additives and household chemicals, provided that purity and granulometric requirements are met.

However, most studies focus on individual utilization pathways without considering the overall material flow system of the enterprise. The integration of screening utilization with other environmental measures remains insufficiently addressed.

In recent years, carbon capture and utilization (CCU) technologies have gained significant attention as tools for reducing industrial carbon emissions. The main approaches discussed in the literature include:

- absorption-based $CO_2$ capture;
- adsorption methods;
- membrane separation technologies;
- mineral carbonation;
- $CO_2$ utilization in chemical synthesis and construction materials **(Scrivener et al., 2018; Gartner & Sui, 2018; Shi et al., 2011; Provis, 2018; Meyer, 2009; Zhilkibayeva, 2024; Bekturganova, 2023; Irgibayev, 2023)**.

Mineral carbonation is of particular interest, as it enables the permanent binding of $CO_2$ in stable solid phases and is considered a promising long-term carbon sequestration mechanism **(Lackner, 2003; Leung et al., 2014)**.

Critical Analysis: While Scrivener et al. (2018) and Habert et al. (2020) provide comprehensive decarbonization strategies for the cement industry, their approaches are less applicable to standalone lime production due to differences in gas flow characteristics and $CO_2$ concentrations. Similarly, studies on limestone screening utilization **(De Weerdt et al., 2011; Chen et al., 2014)** focus on material properties without accounting for the carbon footprint of the processing cycle. Unlike these fragmented approaches, the present study proposes a closed-loop system where screenings serve as both a construction material and a potential sorbent for captured $CO_2$, thereby addressing both waste and emission challenges simultaneously.

Nevertheless, most CCU studies are focused on the cement industry or large-scale energy systems. The specific features of carbonate processing industries-such as gas flow characteristics, $CO_2$ concentrations, and the availability of mineral by-products-are only partially addressed in the literature **(Hills et al., 2016; Habert et al., 2020; Scrivener et al., 2018)**.

Overall, the analysis shows that mineral waste utilization and carbon management technologies are typically developed independently. There is a lack of integrated studies that consider limestone screenings processing and $CO_2$ capture as elements of a unified technological system.

A comprehensive model linking material flows from crushing and calcination, fine fraction generation, gas cleaning processes, and $CO_2$ utilization within the same production cycle is currently absent.

As a result, environmental solutions remain fragmented and provide limited effectiveness.

Within the framework of circular economy principles, there is a growing need to develop integrated models for managing technogenic flows. This study aims to address this gap by proposing an integrated approach combining limestone screening utilization, wet gas cleaning, and CCU technologies into a unified mineral-carbon loop.

## 2 MATERIALS AND METHODS

The object of the study is the technological cycle of carbonate rock (limestone) processing, including crushing, classification, calcination, and flue gas cleaning.

The subject of the study is the material (solid and particulate) and carbon flows generated during limestone processing, as well as the potential for their integrated management within a unified technological system.

A typical scheme of mineral and gaseous flow formation is shown in **Figure 1**, illustrating the key environmental and carbon-related challenges of the industry.

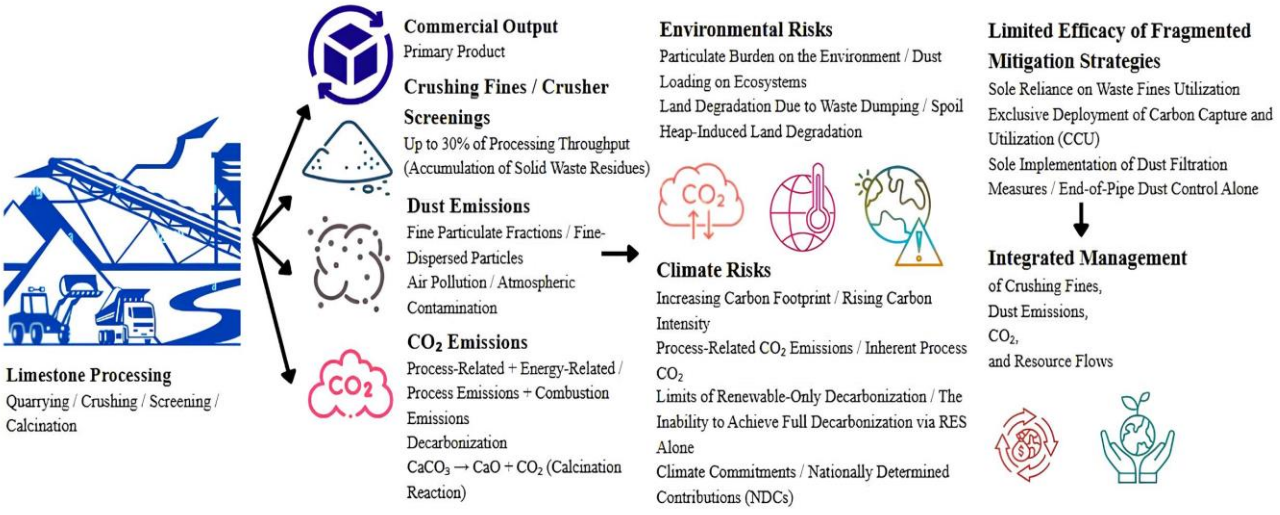

**Figure 1** – Environmental challenges associated with limestone processing and rationale for the implementation of an integrated approach (author's materials).

The study is analytical and conceptual in nature and is based on:

- analysis of scientific publications on decarbonization and carbonate material processing;
- examination of typical technological schemes;
- material flow balance analysis;
- comparative assessment of environmental strategies;
- conceptual modeling of an integrated mineral–carbon loop.

Material flow distribution during crushing and classification is illustrated in **Figure 2**, where fine fractions (screenings) may reach 30–35% of the raw material.

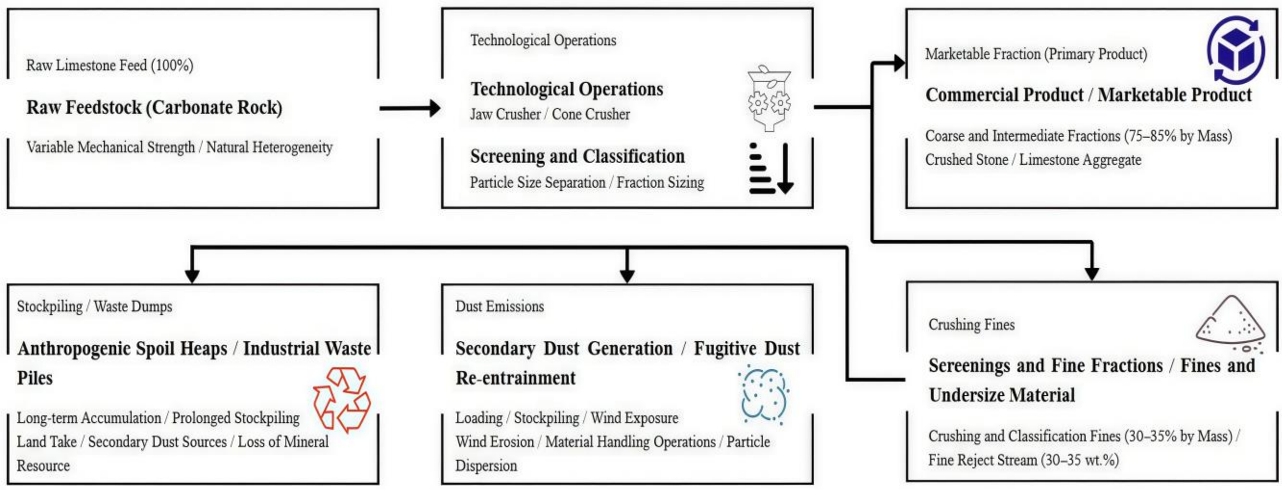

**Figure 2 –** Material flow distribution in limestone processing and formation of limestone screenings (author's materials).

The efficiency of screening utilization is summarized in **Table 1** and **Figure 3**.

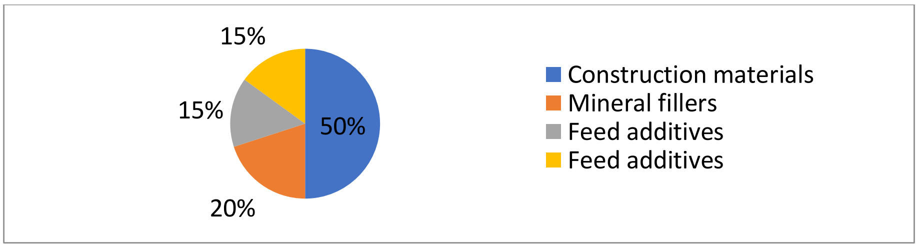

**Figure 3 –** Distribution of reuse pathways for processed limestone screenings (author's materials).

**Table 1**
Comparative Characteristics of Baseline and Integrated Scenarios for Limestone Screenings Management (author's materials)

| **Parameter** | **Baseline Scenario (Landfilling)** | **Integrated Scenario (Processing)** |
|---|---|---|
| Share of utilized screenings, % | < 20 | 85–95 |
| Dust load | High | Significantly reduced |
| Production of secondary products | Absent | Yes |
| Potential economic value | Low | Medium–High |
| Environmental effect | Negative | Positive |

$CO_2$ emission structure is analyzed and presented in **Figure 4**, distinguishing between process and energy emissions.

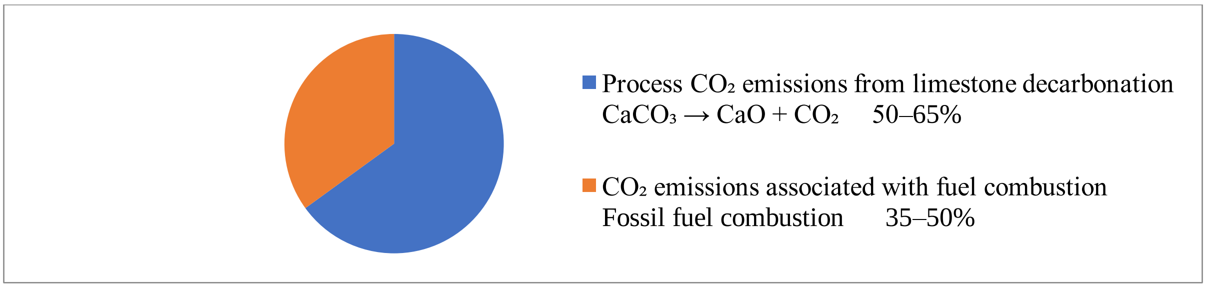

**Figure 4 –** $CO_2$ emission structure in the processing of carbonate rocks (author's materials).

Two scenarios are modeled (**Figure 5**): landfill disposal and secondary utilization.

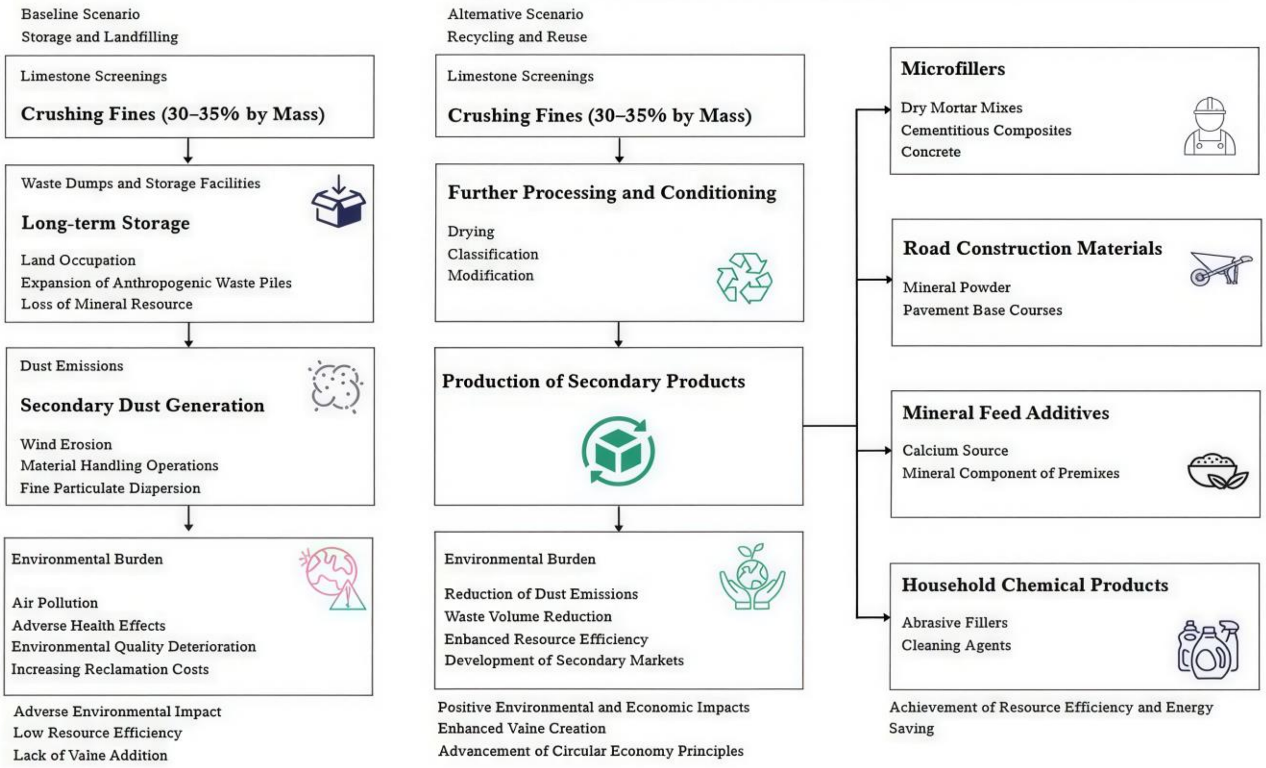

**Figure 5 –** Management scenarios for limestone screenings: landfilling and reuse (author's materials)

Wet gas cleaning using vortex scrubbers is incorporated into the integrated model. Industrial data indicate dust removal efficiency of 98–99.9%, with closed-loop water circulation and no wastewater generation. Captured sludge can be returned to the process, enhancing resource efficiency **(Hamidullina N.A. et al. 2017; Akmalaiuly K. et al. 2025)**.

The integrated concept is illustrated, comparative strategy assessment is shown in **Figure 6**.

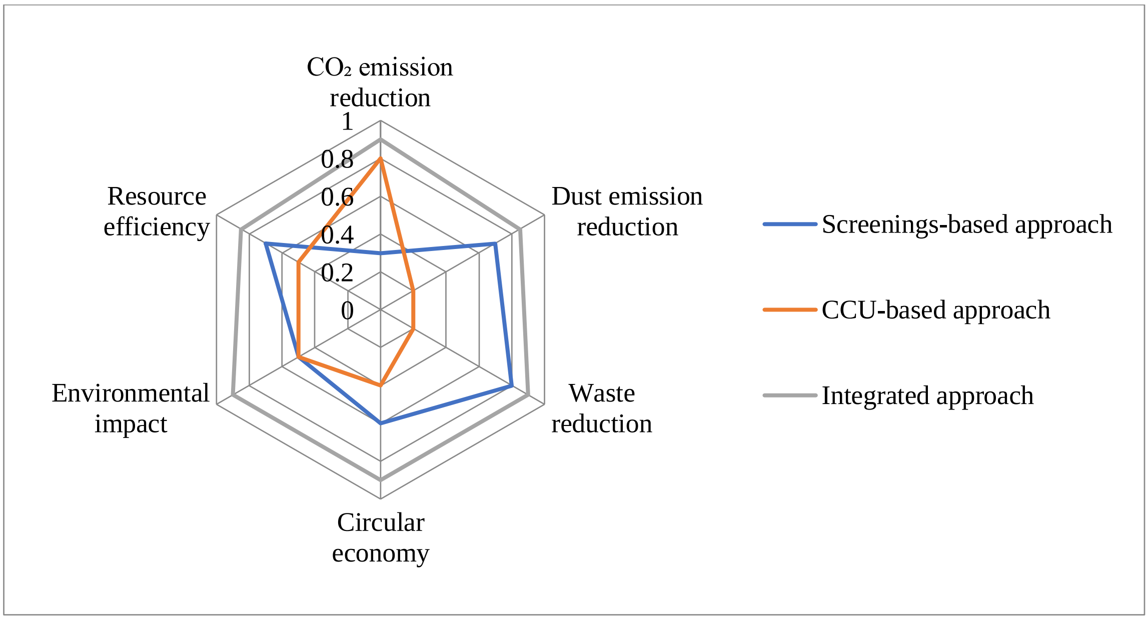

**Figure 6 –** Comparative evaluation of fragmented and integrated approaches to screenings utilization and $CO_2$ emissions management (author's materials).

The effectiveness of the strategies was evaluated based on the following generalized criteria: the share of screenings utilized (%); reduction in waste disposal volumes; reduction in dust emissions; $CO_2$ capture potential; reduction in the overall carbon footprint; and compliance with circular economy principles.

A qualitative comparative assessment based on these criteria was used to construct the generalized graphical representation (**Figure 7**).

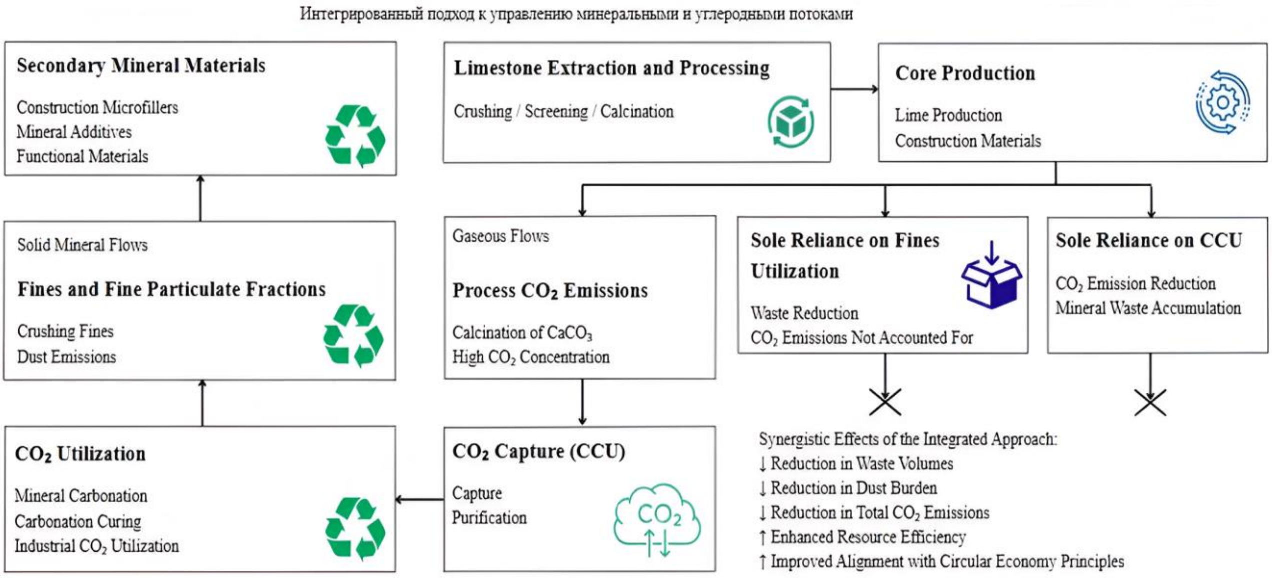

**Figure 7** – Comparative assessment of environmental efficiency of fragmented and integrated strategies for managing mineral and carbon flows (author's materials).

For the quantitative assessment of mineral flow redistribution, a simplified material balance model was applied.

Let: $M_0$ - mass of initial limestone raw material, t; $M_t$ - mass of marketable product fraction, t; $M_r$ - recycled (return) fraction, t; $M_s$ - mass of screenings (fine fraction), t; $M_d$ - dust losses, t.

The overall material balance is expressed as:

$$M_0 = M_t + M_r + M_s + M_d \tag{2}$$

The share of screenings formation is defined as:

$$\alpha_s = \frac{M_s}{M_0} \cdot 100\% \tag{3}$$

According to industrial practice, the value of $\alpha_s$ may reach 30-35%.

Under the integrated processing scheme, a coefficient of screenings utilization is introduced:

$$\eta_s = \frac{M_{s,util}}{M_s} \cdot 100\% \tag{4}$$

where $M_{s,util}$ - is the mass of screenings reused in economic circulation.

In the integrated scenario (**Figure 3 and 6**), the target value of $\eta_s$ is 85–95%, which allows minimizing the volume of landfilled waste:

$$M_{s,landfill} = M_s(1 - \eta_s) \tag{5}$$

Process-related emissions are determined by the stoichiometry of the decarbonization reaction:

$$CaCO_3 \overset{t}{\rightarrow} CaO + CO_2 \uparrow. \qquad (6)$$

Molar masses: $CaCO_3$ = 100 g/mol; $CO_2$ = 44 g/mol.

Thus, the theoretical $CO_2$ fraction in limestone is: $\beta=44/100=0.44$. Accordingly, calcination of 1 ton of pure $CaCO_3$ produces: $E_{proc}=0.44$ т $CO_2$

Considering the carbonate content in raw material γ (typically 0.90–0.98):

$$E_{proc} = 0.44 \cdot \gamma \cdot M_0 \qquad (7)$$

Total emissions are defined as:

$$E_{total} = E_{proc} + E_{fuel} \qquad (8)$$

where: $E_{fuel}$ - энергет represents fuel-related emissions.

The share of process emissions is:

$$\delta_{proc} = \frac{E_{proc}}{E_{total}} \cdot 100\% \qquad (9)$$

Analytical estimates show that $\delta_{proc}$ may reach 55–65%, confirming the limited effectiveness of purely energy-based decarbonization measures (**Figure 5**).

With the implementation of $CO_2$ capture technologies, the capture efficiency is defined as:

$$\eta_{CCU} = \frac{E_{captured}}{E_{proc}} \cdot 100\% \qquad (10)$$

where $E_{captured}$ - is the amount of captured $CO_2$.

Residual emissions are calculated as:

$$E_{residual}=E_{total}-E_{captured} \qquad (11)$$

The overall reduction in carbon footprint is expressed as:

$$R_{CO_2} = \frac{E_{captured}}{E_{total}} \cdot 100\% \qquad (12)$$

For comparative analysis of fragmented and integrated strategies (**Figure 7**), a generalized environmental performance index is proposed:

$$I_{eco} = \omega_1\eta_s + \omega_2\eta_{CCU} + \omega_3\Delta P + \omega_4\Delta L \qquad (13)$$

where: $\eta_s$ - screenings utilization rate; $\eta_{CCU}$ - $CO_2$ capture efficiency; ΔP - reduction in dust emissions; ΔL - reduction in landfill volume; $\omega_i$ - weighting coefficients.

Under the integrated approach, the value of $I_{eco}$ is significantly higher, as illustrated in **Figure 7**.

## 3 RESULTS AND DISCUSSION

The material balance analysis shows that processing $M_0$=1.0 million tons/year of limestone results in screenings generation of $M_s$=0.30-0.35 million tons/year. Even at the lower bound (30%), annual screenings reach 300 thousand tons, creating substantial pressure on land resources under conventional disposal practices. The distribution of material flows during crushing and classification is shown in **Figure 2**. Fine fractions are mainly generated at secondary and tertiary crushing stages, where the proportion of particles smaller than 5 mm increases.

With the implementation of the integrated processing scheme (**Figure 3 and 6**), the utilization rate of screenings can reach 85-95%. Consequently, landfill volumes decrease to 15-45 thousand tons/year, which is 6-10 times lower than the initial amount. These results confirm the high resource efficiency potential of integrated screenings processing. Furthermore, the incorporation of limestone screenings into construction composites reduces the demand for virgin raw materials, aligning with the principles of resource conservation advocated in recent studies **(Zhilkibayeva, 2024; Bekturganova, 2023)**.

Calculation of process emissions for 1 million tons of limestone (with $CaCO_3$ content of 95%) yields: $E_{proc}=0.44\cdot 0.95\cdot 1.0=0.418$ million tons $CO_2$. Thus, process decarbonization alone generates approximately 418 thousand tons of $CO_2$ annually **(Leung et al., 2014; IEA, 2018)**. Including fuel emissions, total emissions may exceed 0.6-0.7 million tons $CO_2$ per year (**Figure 5**). The process component accounts for 55-65% of total emissions, confirming the limited effectiveness of energy-efficiency-only strategies **(Habert et al., 2020; Monteiro et al., 2017)**.

With 60% capture efficiency: $E_{captured}=0.60\cdot 0.418=0.251$ million tons $CO_2$ **(Lackner, 2003; Leung et al., 2014; Hills et al., 2016)**. Residual emissions are reduced by more than 250 thousand tons annually. This level of reduction is significant for regional carbon management plans, particularly in the context of Kazakhstan's strategy to achieve carbon neutrality by 2060. The captured $CO_2$ can be utilized for mineral carbonation, where it reacts with calcium-rich screenings to form stable carbonates, effectively sequestering carbon in building materials **(Scrivener et al., 2018; Gartner & Sui, 2018)**.

Comparative Analysis: The achieved screening utilization rate of 85–95% exceeds the values reported by Zhilkibayeva (2024) for modified binders (approximately 60–70%), primarily due to the diversified application pathways including road construction and mineral fillers. Similarly, the $CO_2$ reduction potential of 30–40% aligns with findings by Lackner (2003) for mineral carbonation, but offers additional benefits through simultaneous dust suppression.

Comparative analysis shows:

Fragmented strategy - partial effect, either waste or emissions remain high. In this case, only a partial environmental effect is achieved, while significant volumes of waste disposal or a high residual carbon footprint remain.

The integrated strategy includes: the utilization of screenings in the production of secondary materials; wet gas cleaning with simultaneous reduction of dust emissions; and $CO_2$ capture and utilization.

A comparative assessment is presented in **Figure 7** (closed mineral–carbon loop). The results show that the integrated model provides: a reduction in waste disposal volumes by 85–95%; a decrease in dust emissions due to wet gas cleaning; a reduction in total $CO_2$ emissions by 30–40% (depending on the capture efficiency); and the generation of additional secondary products.

Analysis of the schemes presented in **Figure 6 and 7** highlights the key systemic effect-closing the material and carbon loops within the production cycle. Screenings and fine particulate fractions are used as raw materials for secondary products, while the captured $CO_2$ can be: directed to mineralization; utilized in construction materials; applied in chemical processes; or reintegrated into the technological cycle. Thus, a unified system is formed in which the demand for primary resources is reduced, waste volumes are minimized, and the overall carbon footprint is lowered.

From an economic perspective, the integrated approach offers additional value streams. The production of mineral fillers and modified binders from screenings **(Zhilkibayeva, 2024)** can offset the operational costs associated with CCU technologies. Although carbon capture imposes an energy penalty, the utilization of waste heat from calcination processes for solvent regeneration in absorption units can mitigate this impact. Moreover, the reduction in landfill taxes and environmental penalties enhances the financial viability of the proposed scheme.

Technically, the integration of wet gas cleaning with CCU allows for the simultaneous removal of particulate matter and $CO_2$. Vortex scrubbers, known for their high dust removal efficiency (98–99.9%) **(Hamidullina et al., 2017; Irgibayev, 2023)**, can be adapted with chemical solvents to capture $CO_2$ from the flue gas stream. This dual-functionality reduces the need for separate equipment trains, lowering capital expenditure. However, challenges remain regarding the stability of solvent performance in the presence of dust and the management of liquid waste streams. Closed-loop water circulation systems, as modeled in this study, address the latter concern by preventing wastewater generation.

The obtained results confirm that the isolated implementation of individual environmental measures does not provide maximum efficiency. Only the integration of mineral waste processing and $CO_2$ management technologies creates a synergistic effect, resulting in the simultaneous reduction of material load, dust emissions, and carbon footprint. This finding is consistent with global trends towards industrial symbiosis and circular economy models **(Provis, 2018; Meyer, 2009)**.

From the perspective of circular economy principles, the integrated model corresponds to the concept of closed-loop production systems and efficient resource utilization **(Zhilkibayeva, 2024; Bekturganova, 2023; Irgibayev, 2023; Akmalaiuly et al., 2025)**. Future research should focus on pilot-scale validation of the proposed integrated scheme and detailed techno-economic analysis to optimize the balance between capture efficiency and energy consumption.

## 4 CONCLUSIONS

1. It has been established that limestone processing generates significant volumes of screenings, accounting for up to 30–35% of the initial raw material mass, corresponding to 300–350 thousand tons annually for a 1 million ton/year capacity. Process-related $CO_2$ emissions based on the decarbonization reaction ($CaCO_3 \rightarrow CaO + CO_2$) reach approximately 0.418 t per ton of processed raw material (95% $CaCO_3$ content), accounting for 55–65% of the total carbon footprint.

2. Material balance modeling demonstrates that the implementation of an integrated processing scheme allows for the utilization of 85–95% of limestone screenings in secondary applications. This reduces the volume of landfilled waste by more than 6–10 times compared to a fragmented management approach, significantly alleviating pressure on land resources.

3. The implementation of carbon capture and utilization (CCU) technologies with a capture efficiency of approximately 60% of process emissions enables a reduction in total $CO_2$ emissions by more than 30–40%. This confirms the limited effectiveness of measures based solely on energy efficiency improvements and necessitates specialized carbon management solutions.

4. Comparative analysis shows that the highest efficiency is achieved through the formation of an integrated mineral–carbon loop that combines solid waste processing, wet gas cleaning, and $CO_2$ capture. The proposed concept is consistent with the principles of circular economy and sustainable development, serving as a methodological basis for further applied research and industrial implementation.

## REFERENCES

1. **Lackner, K. S.** (2003). A guide to $CO_2$ sequestration. Science, 300, 1677–1678. https://doi.org/10.1126/science.1079033
2. **Leung, D. Y. C., Caramanna, G., & Maroto-Valer, M. M.** (2014). An overview of current status of carbon dioxide capture and storage technologies. Renewable and Sustainable Energy Reviews, 39, 426–443. https://doi.org/10.1016/j.rser.2014.07.093
3. **Hills, T., Leeson, D., Florin, N., & Fennell, P.** (2015). Carbon Capture in the Cement Industry: Technologies, Progress, and Retrofitting. Environmental Science and Technology 50(1). https://doi.org/10.1021/acs.est.5b03508
4. **International Energy Agency.** (2018). Technology roadmap: Low-carbon transition in the cement industry. Paris: IEA.
5. **Habert, G., Miller, S. A., John, V. M., Provis, J. L., Favier, A., Horvath, A., & Scrivener, K.** (2020). Environmental impacts and decarbonization strategies in the cement and concrete

industries. Nature Reviews Earth & Environment, 1, 559–573. https://doi.org/10.1038/s43017-020-0093-3

6. **Scrivener, K. L., John, V. M., & Gartner, E. M.** (2018). Eco-efficient cements: Potential economically viable solutions for a low-$CO_2$ cement-based materials industry. Cement and Concrete Research, 114, 2–26. https://doi.org/10.1016/j.cemconres.2018.03.015
7. **Gartner, E., & Sui, T.** (2018). Alternative cement clinkers. Cement and Concrete Research, 114, 27–39. https://doi.org/10.1016/j.cemconres.2017.02.002
8. **Shi, C., Jiménez, A. F., & Palomo, A.** (2011). New cements for the 21st century: The pursuit of an alternative to Portland cement. Cement and Concrete Research, 41, 750–763. https://doi.org/10.1016/j.cemconres.2011.03.016
9. **Provis, J. L.** (2018). Alkali-activated materials. Cement and Concrete Research, 114, 40–48. https://doi.org/10.1016/j.cemconres.2017.02.009
10. **Meyer, C.** (2009). The greening of the concrete industry. Cement and Concrete Composites, 31, 601–605. https://doi.org/10.1016/j.cemconcomp.2008.12.010
11. **Monteiro, P. J. M., Miller, S. A., & Horvath, A.** (2017). Towards sustainable concrete. Nature Materials, 16, 698–699. https://doi.org/10.1038/nmat4930
12. **De Weerdt, K., Kjellsen, K. O., Sellevold, E., & Justnes, H.** (2011). Synergy between fly ash and limestone powder in ternary cements. Cement and Concrete Composites, 33(1), 30–38. https://doi.org/10.1016/j.cemconcomp.2010.09.006
13. **Irassar, E. F., Bonavetti, V. L., & Menéndez, G.** (2001). Limestone filler in cement: Effect on early-age hydration and strength. Cement and Concrete Research, 31, 853–859. https://doi.org/10.1016/S0008-8846(01)00491-4
14. **Chen, J. J., Ng, P. L., Kwan, A. K. H., & Li, L. G.** (2014). Use of Limestone Fines to Reduce Permeability of Concrete for Durability Improvement. American Journal of Civil Engineering 4(4):185-190. https://doi.org/10.11648/j.ajce.20160404.18
15. **Hamidullina, N. A., Makhotkin, A. F., Makhotkin, I. A., & Bakirov, N. G.** (2017). Comprehensive solution to the problem of processing limestone fine stone waste and wet cleaning of exhaust gases from dust [Kompleksnoe reshenie problemy pererabotki otkhodov melkogo kamnya izvestnyaka i mokroi ochistki otkhodyashchikh gazov ot pyli]. Vestnik Tekhnologicheskogo Universiteta, 20(7), 64–66. (In Russ.)
16. **Kazhetaev, A. S., Rustemov, I. A., & Yelemes, D. Y.** (2025). Comprehensive utilization of limestone crushing screenings in road construction. In Proceedings of the International Conference "Strategies, Materials and Technologies for Sustainable and Decarbonized Road Construction and Road Maintenance (TC 4.5)" (pp. 19–22). Almaty, Kazakhstan.
17. **Estemesova, A. S., Zhilkibayeva, A. M., & Matveeva, L. Yu.** (2024). Study of the properties of modified binder obtained from mining waste [Issledovanie svoystv modifitsirovannogo vyazhushchego, poluchennogo iz otkhodov gornodobyvayushchey promyshlennosti]. Bulletin of the Kazakh Leading Academy of Architecture and Civil Engineering, 2(92), 22–35. https://doi.org/10.51488/1680-080X/2024.2-02 (In Russ.)
18. **Zhilkibayeva, A. M.** (2024). Construction and operational properties of concretes based on modified binder [Stroitelnye i ekspluatatsionnye svoystva betonov na modifitsirovannom vyazhushchem]. Bulletin of the Kazakh Leading Academy of Architecture and Civil Engineering, 2(92), 36–49. https://doi.org/10.51488/1680-080X/2024.2-03 (In Russ.)
19. **Kolesnikova, I. V., Suvorov, A. S., & Bekturganova, N.** (2023). Analysis of prospects for using local raw materials to obtain self-compacting concrete in the Republic of Kazakhstan [Qazaqstan Respublikasynda ózini-ózi tygyzdaıtyn betondardy alu úshin jergilikti shıkizatty paıdalanu perspektivalaryn taldaý]. Bulletin of the Kazakh Leading Academy of Architecture and Civil Engineering, 4(90), 91–105. https://doi.org/10.51488/1680-080X/2023.4-08 (In Kaz.)
20. **Irgibayev, T., Nurpeisova, M. B., & Kulembayev, Y. T.** (2023). Development of energy-efficient air dedusting technology in metro systems [Razrabotka energoeffektivnoy tekhnologii vozdukhoochistki v sistemakh metro]. Bulletin of the Kazakh Leading Academy of Architecture and Civil Engineering, 4(90), 78–90. https://doi.org/10.51488/1680-080X/2023.4-07 (In Russ.)
21. **Akmalaiuly, K., Kanarbay, A. U., Rakhimdzhanov, D. M., & Berdikul, N. I.** (2025). 3D printing of fine-grained concrete with nano-mixture [Nano-qospamen uaq tüıirshikti betondy 3D basyp shyğaru]. Bulletin of the Kazakh Leading Academy of Architecture and Civil Engineering, 2(96), 63–74. https://doi.org/10.51488/1680-080X/2025.2-06 (In Kaz.)