# Processing used Aluminium Production Granular Filters to Produce Concrete

**Petr O. Bykov**
Toraighyrov University, Pavlodar, Kazakhstan
bykov.p@teachers.tou.edu.kz

**Almaz B. Kuandykov**
Toraighyrov University, Pavlodar, Kazakhstan
azeka200892@mail.ru (corresponding author)

**Ainagul B. Kaliyeva**
Toraighyrov University, Pavlodar, Kazakhstan
kalieva.a@teachers.tou.edu.kz

**Eduard Siemens**
Anhalt University of Applied Sciences, Kothen (Anhalt), Germany
eduard.siemens@hs-anhalt.de

*Received: 22 October 2024 | Revised: 23 November 2024 | Accepted: 27 November 2024*

 *DOI: https://doi.org/10.48084/etasr.9360*

**ABSTRACT**

**This article presents the findings of experimental studies on the involvement in the processing of spent filters from ash and slag waste used in the refining of primary aluminum as a filler for concrete production. The processing of spent granular filters was conducted in three stages. The first stage involved the preliminary processing of filter grains to remove aluminum scrap. The second stage entailed the metallurgical processing of separated aluminum scrap through remelting in an induction crucible furnace and subsequent refining. The third stage focused on the production of a concrete mixture comprising crushed spent filter grains, quartz sand, bauxite sludge, screenings of crushed rocks with a fraction of 20 mm–30 mm, and Portland cement. This mixture was used to create samples of building products. The test results indicate that the tensile strength of the concrete samples for building products ranges from 20.89 MPa to 37.75 MPa, depending on the Portland cement content. This strength corresponds to that of heavy concrete.**

***Keywords-metallurgy; aluminum; ecology; granular filters; recycling***

## I. INTRODUCTION

In recent years, numerous studies have been conducted globally on the purification of primary aluminum from impurities of heavy non-ferrous metals, including vanadium, which is associated with the deterioration in the quality of raw materials for the production of anodes for aluminum electrolyzers [1-8]. In the aforementioned works, the authors conducted comprehensive studies to ascertain the mechanism of formation of vanadium intermetallic compounds during the treatment of aluminum melt with boron. Authors in [2] demonstrated that the chemical reactions occurring in the Al-V-B system are highly complex and that the system is most thermodynamically stable when the operating temperature for electrolysis and pouring of aluminum is between 950 °C and 650 °C, resulting in the formation of vanadium diboride ($VB_2$) compounds. The kinetics of the chemical reactions involved in the formation of $VB_2$ compounds during the refining process with Al-B-based ligatures is characterized by a low rate due to the formation of an insoluble ring of reaction products consisting of $VB_2$. As the melt holding time increases to 720 minutes, the thickness of the ring increases from 1 μm to 20 μm [2–4]. Authors in [5] employed boric acid ($H_3BO_3$) as a refining agent for aluminum from vanadium, with the addition of the acid to the electrolysis bath. The implementation of this methodology in industrial settings may potentially lead to reduced durability of the electrolyzer bottom and diminished current efficiency in the aluminum electrolysis process, due to the accumulation of vanadium intermetallic compounds formed on the electrolyzer bottom. Authors in [6] infused boric acid into the anode mass during the production of baked anodes and during aluminum electrolysis. This resulted in the transfer of boron into the aluminum melt, which contributed to a reduction in the vanadium content within the melt. This method is similarly flawed in comparison to the previous method. The technology of refining primary aluminum from vanadium impurities with boron-containing materials, Al-B ligature and boric acid H3BO3, outside the electrolysis bath was examined in [7, 8]. The specific studies revealed a reduction in the vanadium content by an average of 55–78% in the metal mass, an uneven distribution of vanadium in the ladle volume following the refining process, and the challenge of separating vanadium intermetallic compounds and refined aluminum in the ladle using conventional techniques. The latter was evidenced by the fact that settling for four to seven hours yielded no positive outcome. One of the most promising methods of cleaning primary aluminum from impurities, in conjunction with flux refining, is filtration. A review of the literature on the thermodynamic foundations of filtration processes [9–15], reveals that the efficiency of separating inclusions varies significantly depending on the filter material and the filtration scheme employed.

Authors in recent studies [9, 10] propose a Reaction-Crystallization Mechanism (RCM) for melt filtration. The RCM scheme comprises the following stages: the delivery of the impurity to be removed to the filter surface and the component that binds it, their adsorption on the filter surface, and a chemical reaction between them. Subsequently, a non-metallic or phase is released, which can accumulate on the surface, or be absorbed into the filter pores. However, the use of ceramic filters results in the generation of a considerable quantity of new waste at primary aluminum production facilities, in the form of used filters. The environmental factor is of significant importance, exerting considerable influence on the development of individual metallurgical technologies worldwide, including in Kazakhstan. In the last few years, the Republic of Kazakhstan has enacted foundational legislation that charts the course for the advancement of metallurgical enterprises in the following domains [16-18]: the necessity for the development of a green economy and the creation of closed production cycles, coupled with the development of an effective waste management system. This system should facilitate the constant circulation of materials throughout the production and consumption processes, thereby eliminating the accumulation of waste in the environment. Authors in [7, 13] examined a comprehensive technology for refining primary aluminum from vanadium and other metallic impurities using flux and filtration refining based on boric acid. The findings of the studies indicate that the comprehensive technology for refining raw aluminum from vanadium using boric acid ($H_3BO_3$) in a ladle with subsequent filtration enables a reduction in the content of non-ferrous metal impurities in primary aluminum. Laboratory studies have demonstrated a reduction in the concentration of vanadium by 47.7%, copper by 17.6%, magnesium by 47.5%, manganese by 50.0%, and silicon by 97.9% in primary aluminum subjected to flux refining with H3BO3 and a subsequent near-complete removal of the reaction products of non-ferrous metal impurities with boron, based on the findings of the filtration process [7, 13].

In these studies, the material used for the production of filter grains was Ekibastuz coal ash, which is primarily composed of $SiO_2$ and $Al_2O_3$, as presented in Tables I and II.

TABLE I. CHEMICAL COMPOSITION OF EKIBASTUZ COAL ASHES (%)

| $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | FeO | $TiO_2$ | CaO | MgO | $SO_3$ | l.oi. | Hygr. water | $CO_2$ | ≤ $SiO_2$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 46.7 | 25.2 | 6.58 | 0.66 | 1.28 | 7.66 | 3.1 | 1.26 | 3.41 | 0.57 | 3.96 | 26.7 |

TABLE II. PHASE-MINERALOGICAL COMPOSITION OF EKIBASTUZ COAL ASHES, WT. (%) (AVERAGE)

| Glass phase | Amorphized clay substance | Iron oxides | Feldspar, quartz, pyroxene | Corundum, mullite, cristobalite | Calcite | Carbonaceous particles |
|---|---|---|---|---|---|---|
| 30 | 25 | 9 | 10 | 7 | 8 | 11 |

The results of the conducted studies indicate that the filtration refining process results in the formation of a considerable quantity of waste in the form of spent grains with a diameter of 15 mm-25 mm and aluminum scrap. The mean filter consumption was found to be 0.2%–0.5% of the mass of the poured metal. Consequently, during the production of primary aluminum at the Kazakhstan Electrolysis Plant JSC, where up to 268 thousand tons per year are produced, the mass of the spent filters will amount to up to 1,340 tons. As indicated in [18], the remuneration for the emissions of pollutants from stationary sources of this category of waste, ash and slag, in the Republic of Kazakhstan is approximately $7 US per ton. The total annual fee for emissions of 1,340 tons of this waste is therefore approximately $10,000 US. A review of the literature reveals that ash, slag, and other waste materials with similar chemical and mineralogical compositions are frequently used in the production of building products [19–31]. Authors in [19, 22] examine the practices of Ecostroy NII-PV LLC in processing man-made waste from the energy and metallurgy industries of the Pavlodar region of the Republic of Kazakhstan for use in the manufacture of building products. The technology employed uses local waste materials, including ash and slag waste from the combustion of Ekibastuz coal, bauxite sludge from the Pavlodar Aluminum Plant, and steelmaking slag. These materials exhibit distinctive chemical and granulometric compositions, as well as binding properties, when compared to analogous mixtures. The existing literature [20, 23–26, 28] addresses the issue of steel smelting and its concomitant formation of steelmaking slags. Moreover, authors in [20] addressed the topic of incorporating primary steelmaking slag into processing, specifically the extraction of cast iron and the subsequent production of slag, which was used in the manufacture of building products. Primary steel slag is not currently employed in the production of building products due to its high iron content, with its use being confined to road construction.

Authors in [21] explored the technological processes involved in the production of expanded clay granules from coal mining waste. The authors posit that the production of granular porous fillers based on crushed fractions of igneous rocks-basalt, granite, and syenite, as well as artificial materials of various origins, is a promising path of research. The findings of the studies indicated that the optimal range of waste in expanded clay was 4.0%-6.0%, with the optimal heating temperature being 1150°C. This resulted in the production of samples with a bulk density of 0.337 t/m³-0.348 t/m³ and a compressive strength, under the aforementioned conditions, of

1.37 MPa-1.51 MPa. Authors in [27] presented the results of obtaining clinkers from sulfate-resistant and road cement during production tests. The present paper analyses the use of man-made waste, lead slag, and coal mining waste, as a clay component and additive. The paper identifies patterns of influence of the batch compositions and firing modes on the chemical and mineralogical composition and quality of clinkers and cements, thereby enhancing the operation of a rotary kiln, reducing greenhouse gas emissions, and optimizing fuel consumption. The strength of the factory and experimental cements was evaluated at 3, 7, and 28 days post-production, as well as following steaming. The physical and mechanical characteristics and structure of cements were subjected to rigorous examination. Low-energy cement mixtures were developed and subjected to testing. Authors in [29] examined the optimization of a three-component raw mix for the production of mixed cement. The optimization was conducted using the ROCS software package, developed by scientists from the Belgorod State Technological University (BSTU), which is designed to calculate and optimize multi-component raw mixes for cement production. The optimal composition of the raw mixes was thus determined. The cement prepared by mixing 57% of regular, 40% of low-basic clinker, and 3% gypsum exhibited enhanced strength, with increases of 7.4% and 27.7%, respectively, in comparison to the strength of the standard cement. Authors in [30] modeled the chemical and phase transformations occurring in the aWaelz process-slag-carbon system, within a temperature range of 1700 K-2100 K and at a pressure of 0.1 MPa. It was determined that the maximum quantity of iron that can be incorporated into condensed $Fe_3Si$ ranges from 34.7% at 1800 K to 99.9% at 2100 K, while in $Fe_5Si_3$, this range is from 47.7% at 1900 K to 45.6% at 2000 K. As temperature increases further, iron begins to transition into the gas phase. In comparison to iron, silicon is more challenging to extract and begins to transition into the gas phase as the temperature increases. The extent of transition of non-ferrous metals, including zinc, cadmium, and lead, into the gas phase is 99.99% across the entire temperature range. The modeling enabled an investigation into the potential for producing ferrosilicon from non-ferrous metallurgical waste via electric arc furnace smelting. Authors in [31] presented a physicochemical study of technogenic waste produced by the mining and metallurgical industries, specifically tailings resulting from the processing of non-ferrous metal ores. In particular, the current state of the mining and metallurgical industry, the problems of formation of technogenic waste, and the sampling of technogenic raw materials in the form of tailings of beneficiation of non-ferrous metal ores with technogenic mineral composition are considered. The methods of studying technogenic waste are presented, including granulometric analysis (using sieve analysis), chemical analysis, electron microscopy (using a JSM-6490LV scanning electron microscope), and X-ray phase analysis (using an ARL X'TRA A X-ray diffractometer). As a result of a series of studies, the coordinates of the corner points of the geological section of the tailings dump were established. This was achieved through the application of physicochemical methods of analysis to technogenic waste from the beneficiation of the mining and metallurgical industry. A review of the scientific literature revealed that the issue of recycling spent filters from aluminum production remains unresolved and necessitates further investigation to identify optimal processing options for their usage in the metallurgical industry. This article addresses the potential for incorporating spent filters from ash and ash-slag waste, which are currently used in the refining of primary aluminum, into the production of concrete for the manufacture of building materials.

## II. RESEARCH METHODS

The study focused on granular filters derived from the combustion of Ekibastuz coal in North-East Kazakhstan. The filters were obtained from the ash of the coal after it was heated in coal-fired power plants. The processing of spent granular filters was conducted in three stages:

- The preliminary processing of the filter grains involved the removal of aluminum scrap, as shown in Figure 1. This entailed grinding the granules in a drum mill and classifying the metallic and non-metallic parts of the processed material.
- The separated aluminum scrap was then subjected to metallurgical processing through remelting in an induction crucible furnace. Refining was conducted using the integrated technology described in [7].
- A concrete mixture was obtained based on crushed spent filter grains, quartz sand, bauxite sludge, and screenings of crushed rocks with a fraction of 20 mm–30 mm, with Portland cement added to produce samples of building products.

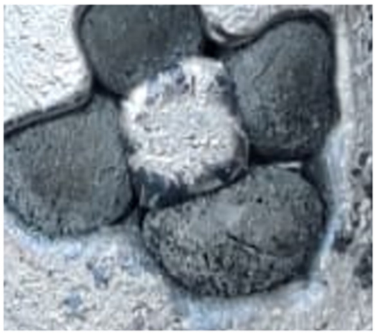

Fig. 1. General view of used filters.

In an effort to reduce the reliance on quartz sand, crushed spent filter grains were employed as a filler for the concrete mixture, with a maximum volume of 30% of the total material consumption. This approach was based on the findings of earlier studies [19-21]. The water-to-cement ratio was set at 0.35. The production of construction samples and products was conducted at EcostroyNII-PV LLP through the usage of the vibration pressing method on the Rifey-Udar-SDA production line. This method has been extensively employed at the aforementioned facility, and has been developed to incorporate innovative solutions in the field of industrial waste utilization in production [19, 22]. The construction products were subjected to testing at the Incom Company LLP laboratory, complying with the GOST ISO/IEC 17025-2019 standard.

## III. RESEARCH RESULTS AND DISCUSSION

Table III presents the compositions of the concrete mixtures. To facilitate the assessment of the samples, supplementary cube molds with dimensions of 100 mm × 100 mm × 100 mm were fabricated, as seen in Figure 2. In this study, the density and strength of the samples were determined. The density of the concrete samples was determined in accordance with the standards set forth in GOST 12730.1-78, and the results of this analysis are presented in Table IV. The compressive strength of the concrete was determined using a P-10 press at a concrete age of 28 days, as displayed in Figure 3, and the test results are outlined in Table V.

TABLE III. CONCRETE MIXTURE COMPOSITIONS USING SPENT GRANULAR FILTERS

| Concrete mix batch number | Mass fraction of cement (%) | Mass fraction of sand (%) | Mass fraction of spent granular filters ASW (%) |
|---|---|---|---|
| 1 | 40 | 60 | 0 |
| 2 | 35 | 55 | 10 |
| 3 | 30 | 50 | 20 |
| 4 | 25 | 45 | 30 |
| 5 | 20 | 40 | 40 |

Fig. 2. Samples for testing.

TABLE IV. DENSITY OF CONCRETE SAMPLES

| Sample mark | Mass fraction of spent granular filters ASW (%) | Density, g/cm$^3$ | Concrete class |
|---|---|---|---|
| 1 | 0 | 2.61 | Heavy concrete |
| 2 | 10 | 2.39 | |
| 3 | 20 | 2.19 | |
| 4 | 30 | 1.95 | |
| 5 | 40 | 1.86 | |

TABLE V. CONCRETE STRENGTH CLASS

| Sample mark | Strength, kg/cm$^2$ | Strength, MPa | Concrete strength class | Concrete grade by strength |
|---|---|---|---|---|
| 1 | 385 | 37.75 | B30 | M400 |
| 2 | 327 | 32.06 | B25 | M350 |
| 3 | 307.6 | 30.16 | B25 | M350 |
| 4 | 235.3 | 23.07 | B20 | M250 |
| 5 | 213.1 | 20.89 | B15 | M200 |

Fig. 3. Determination of the strength of the samples.

The test results indicate that the tensile strength of the concrete samples of building products ranges from 20.89 MPa to 37.75 MPa, with the strength dependent on the Portland cement content, classified as heavy concrete.

## IV. CONCLUSIONS

The results of the conducted experimental studies indicate that it is feasible to use spent filters from ash and ash - slag waste as a filler in the production of concrete for building products. The metallurgical processing of aluminum scrap derived from the grains of spent filters can be achieved through remelting in an induction crucible furnace, followed by the refinement of the metal. The test results indicate that the tensile strength of concrete samples for building products ranges from 20.89 to 37.75 MPa, depending on the Portland cement content (between 20 and 40%), and corresponds to the heavy concrete classification.

## ACKNOWLEDGMENT

The studies were conducted within the framework of grant funding from the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan under the competition "Zhas Galym," under the project IRN AP19175493 “Development of technology for refining primary aluminum with filters with an active surface”.

## REFERENCES

[1] A. T. Ibragimov and R. V. Pack, *Aluminum electrometallurgy. Kazakhstan Electrolysis Plant*. Pavlodar, Kazakhstan, 2009.

[2] A. Khaliq, M. A. Rhamdhani, G. A. Brooks, and J. F. Grandfield, "Removal of Vanadium from Molten Aluminum-Part I. Analysis of VB2 Formation," *Metallurgical and Materials Transactions B*, vol. 45, no. 2, pp. 752–768, Apr. 2014, https://doi.org/10.1007/s11663-013-9974-x.

[3] A. Khaliq, M. A. Rhamdhani, G. A. Brooks, and J. F. Grandfield, "Removal of Vanadium from Molten Aluminum—Part II. Kinetic Analysis and Mechanism of VB2 Formation," *Metallurgical and Materials Transactions B*, vol. 45, no. 2, pp. 769–783, Apr. 2014, https://doi.org/10.1007/s11663-013-9975-9.

[4] A. Khaliq, M. Akbar Rhamdhani, G. A. Brooks, and J. Grandfield, "Removal of Vanadium from Molten Aluminum—Part III. Analysis of Industrial Boron Treatment Practice," *Metallurgical and Materials Transactions B*, vol. 45, no. 2, pp. 784–794, Apr. 2014, https://doi.org/10.1007/s11663-013-0017-4.

[5] E. S. Gorlanov, A. A. Batrachenko, B. Sh.-A. Smailov, and A. Yu. Morozov, "Role of Vanadium in Aluminum Electrolyzer Melts," *Metallurgist*, vol. 62, no. 9, pp. 1048–1053, Jan. 2019, https://doi.org/10.1007/s11015-019-00752-8.

[6] E. S. Gorlanov, A. A. Batrachenko, B. Sh.-A. Smailov, and A. P. Skvortsov, "Testing Baked Anodes with an Increased Vanadium Content," *Metallurgist*, vol. 62, no. 1, pp. 62–69, May 2018, https://doi.org/10.1007/s11015-018-0626-x.

[7] P. O. Bykov, A. B. Kuandykov, and A. K. Zhunusov, "Refining of Primary Aluminum from Vanadium," *Defect and Diffusion Forum*, vol. 410, pp. 405–410, 2021, https://doi.org/10.4028/www.scientific.net/DDF.410.405.

[8] P. O. Bykov, A. B. Kuandykov, A. K. Zhunusov, L. B. Tolymbekova, and M. M. Suyundikov, "Complex processing of primary aluminum to remove impurities of non-ferrous metals," *Metalurgija*, vol. 62, no. 2, pp. 293–295, Apr. 2023.

[9] B. K. Shayakhmetov, B. M. Kimanov, E. B. Ten, A. Z. Issagulov, Z. D. Zholdubayeva, and D. A. Issagulova, "Gravimetric and dilatometric research of elements action on three dimensional filter by themal effects," *Metalurgija*, vol. 53, no. 1, pp. 44–46, Jan. 2014.

[10] S. E. Shipilov *et al.*, "Refining of metal melts by filtration method," *Metalurgija*, vol. 58, no. 3–4, pp. 303–306, Jul. 2019.

[11] S. Bao, "Filtration of Aluminium-Experiments, Wetting,and Modelling," Ph.D. dissertation, Department of Materials Science and Engineering, Norwegian University of Science and Technology, Trondheim, Norway, 2011.

[12] H. Görner, "Removal of dissolved elementsin aluminium by filtration," Ph.D. dissertation, Department of Materials Science and Engineering, Norwegian University of Science and Technology, Trondheim, Norway, 2009.

[13] A. B. Kuandykov, A. G. Bakirov, A. K. Zhunusov, and P. O. Bykov, "Granular filters from Ekibastuz coal ash for refining primary aluminum," *Science and Technology of Kazakhstan*, vol. 4, pp. 80–90, 2022.

[14] A. B. Kuandykov and P. O. Bykov, "Study of refining the first impact from impurities of non-ferrous metals using 'active' granular filters based on boric acids," *Science and Technology of Kazakhstan*, vol. 3, pp. 203–210, 2023.

[15] A. V. Kurdumov, S. V. Inkin, V. S. Chulkov, "Metal impurities in aluminum alloys," 1988.

[16] *On the Concept of the Transition of the Republic of Kazakhstan to a "Green Economy,"* Decree of the President of the Republic of Kazakhstan no. 577. 2013.

[17] *Strategy for achieving carbon neutrality of the Republic of Kazakhstan until 2060*, Decree of the President of the Republic of Kazakhstan no. 121, 2023.

[18] *No.400-VI LRK Environmental Code of the Republic of Kazakhstan*. Almaty, Kazakhstan: Ministry of Justice of the Republic of Kazakhstan, 2021.

[19] K. S. Aryngazin, A. V. Bogomolov, and A. K. Tleulessov, "Innovational Construction Materials of LLP 'EcostroyNII-PV' Production," *Defect and Diffusion Forum*, vol. 410, pp. 806–811, 2021, https://doi.org/10.4028/www.scientific.net/DDF.410.806.

[20] P. Bykov, A. Bogomolov, A. Bitkeyeva, and R. Nurgozhin, "Research of iron extraction from primary steelmaking slag," *Journal of Applied Engineering Science*, vol. 21, no. 4, pp. 1094–1097, Nov. 2023, https://doi.org/10.5937/jaes0-44128.

[21] Y. Kocherov *et al.*, "Investigation of the Physico-Chemical and Mechanical Properties of Expanded Ceramsite Granules Made on the Basis of Coal Mining Waste," *Journal of Composites Science*, vol. 8, no. 8, Aug. 2024, Art. no. 306, https://doi.org/10.3390/jcs8080306.

[22] K. S. Aryngazin, P. O. Bykov, A. K. Aldungarova, A. K. Tleulesov, and A. V. Bogomolov, "Commercialization of scientific research using the example of EcostroyNII-PV LLP," in *Entrepreneurial University - Science, Innovation, Education and Business: collection of scientific works*, Pavlodar, Kazakhstan, 2019, pp. 31–44.

[23] S. H. Abro, H. A. Moria, A. Chandio, and A. Z. Al-Khazaal, "Understanding the Effect of Aluminum Addition on the Forming of Second Phase Particles on Grain Growth of Micro-Alloyed Steel," *Engineering, Technology & Applied Science Research*, vol. 10, no. 1, pp. 5153–5156, Feb. 2020, https://doi.org/10.48084/etasr.3243.

[24] T. Sunar and M. Cetin, "An Experimental Study on Boron Carbide Reinforced Open Cell Aluminum Foams Produced via Infiltration Technique," *Engineering, Technology & Applied Science Research*, vol. 8, no. 6, pp. 3640–3645, Dec. 2018, https://doi.org/10.48084/etasr.2419.

[25] S. K. Ghazi, M. Y. Salloom, and A. S. Bedan, "Experimental Evaluation of a System to Control the Incremental Forming of Aluminum Alloy Type 1050," *Engineering, Technology & Applied Science Research*, vol. 14, no. 5, pp. 16943–16949, Oct. 2024, https://doi.org/10.48084/etasr.8387.

[26] O. Kolesnikova, F. Nurbaeva, G. Sabyrbayeva, and L. Nurshakhanova, "Thermodynamic modeling of the reaction of simultaneous interaction of nickel (II), cobalt (II) and iron (III) oxides with carbon," *E3S Web of Conferences*, vol. 378, 2023, Art. no. 04001, https://doi.org/10.1051/e3sconf/202337804001.

[27] B. T. Taimasov, B. K. Sarsenbayev, T. M. Khudyakova, A. S. Kolesnikov, and N. N. Zhanikulov, "Development and Testing of Low-Energy-Intensive Technology of Receiving Sulphate-Resistant and Road Portlandcement," *Eurasian Chemico-Technological Journal*, vol. 19, no. 4, pp. 347–355, Dec. 2017, https://doi.org/10.18321/ectj683.

[28] A. S. Kolesnikov, V. N. Naraev, M. I. Natorhin, A. A. Saipov, and O. G. Kolesnikova, "Review of the processing of minerals and technogenic sulfide raw material with the extraction of metals and recovering elemental sulfur by electrochemical methods," *RASĀYAN Journal of Chemistry (RJC)*, vol. 13, no. 4, pp. 2420–2428, Dec. 2020.

[29] A. S. Kolesnikov *et al.*, "Review of technogenic waste and methods of its processing for the purpose of complex utilization of tailings from the enrichment of non-ferrous metal ores as a component of the raw material mixture in the production of cement clinker, " *RASĀYAN Journal of Chemistry (RJC)*, vol. 14, no. 2, pp. 997–1005, Jun. 2021, https://doi.org/10.31788/RJC.2021.1426229.

[30] T. M. Khudyakova *et al.*, "Optimization of Raw Material Mixes in Studying Mixed Cements and Their Physicomechnical Properties," *Refractories and Industrial Ceramics*, vol. 60, no. 1, pp. 76–81, May 2019, https://doi.org/10.1007/s11148-019-00312-2.

[31] A. S. Kolesnikov *et al.*, "Thermodynamic Modeling of Chemical and Phase Transformations in a Waelz Process-Slag – Carbon System," *Refractories and Industrial Ceramics*, vol. 61, no. 3, pp. 289–292, Sep. 2020, https://doi.org/10.1007/s11148-020-00474-4.

[32] A. Donayev, A. Kolesnikov, S. Shapalov, B. Sapargaliyeva, and G. Ivakhniyuk, "Studies of waste from the mining and metallurgical industry, with the determination of its impact on the life of the population," *NEWS of National Academy of Sciences of the Republic of Kazakhstan*, vol. 4, no. 454, pp. 55–68, https://doi.org/10.32014/2022.2518-170X.200.


AUTHORS PROFILE

**Petr O. Bykov**, Department of Metallurgy, Toraighyrov University, Pavlodar, Kazakhstan. Candidate of technical sciences (2010), professor of the department "Metallurgy". Research area: Metallurgy, Materials Science and Mechanical Engineering, Ecology. Awarded the medal "For the Development of Science" of the Ministry of Science and Higher Education of the Republic of Kazakhstan (2024), the medal "120 Years of Oil of Kazakhstan" of the Ministry of Energy of the Republic of Kazakhstan (2019), «Gold medal» of S. Toraigyrov for merits in the development of PSU named after S. Toraigyrov (2015). Winner of the competition "The best teacher of the University of the Republic of Kazakhstan" (2017). Honorary diploma of the Ministry of Education and Science of the Republic of Kazakhstan (2014). Academician of the International Academy of Informatization since (2024).

**Almaz B. Kuandykov**, Department of Metallurgy, Toraighyrov University, Pavlodar, Kazakhstanv. Post-doctoral student of the department "Metallurgy" (2020). Research area: Metallurgy, Materials Science. Awarded with special diploma from rector of the Toraighyrov University.

**Ainagul B. Kaliyeva**, Department of Biology and Ecology, Toraighyrov University, Pavlodar, Kazakhstan. Candidate of Biological Sciences, professor and Head of the Department of Biology and Ecology. Research area: Biology, Ecology, Environment and its protection, Entomology, Parasitology. Awarded «Gold medal» of S. Toraigyrov (2019). Winner of the competition «The best teacher of the University of the Republic of Kazakhstan» (2009, 2020). Winner of the scholarship of the International Bolashak Program (2020), of the scientific scholarship of the Ministry of Education and Science of the Republic of Kazakhstan for young scientists (2010, 2015). Laureate of the D. A. Kunaev State Prize for young scientists in the field of natural sciences (2009), the state youth award «Daryn-2012» of the Government of the Republic of Kazakhstan (2012). «Letter of gratitude» of the Ministry of Education and Science of the Republic of Kazakhstan (2018). «Honorary diploma» of the Ministry of Science and Higher Education of the Republic of Kazakhstan (2022). «Gratitude» of the Ministry of Science and Higher Education of the Republic of Kazakhstan (2024).

**Eduard Siemens**, PhD, Future Internet Lab Anhalt (FILA), University for Applied Science - Anhalt, Kothen (Anhalt), Germany. Director of the Doctoral Center for Engineering Sciences and Information Technologies (IWIT), Professorship for communication technologies. Head of the Future Internet Lab Anhalt (FILA), Anhalt University of Applied Sciences.