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Metallurgy

# Use of Industrial By-products from Metallurgical Production for the Development of Heat-Resistant Building Mixes and their Molding in an Improved Device

[1]Khabiyev A.T., [1]Yulussov S.B., [1]Abduraimov A.E., [1]Kamal A.N., [1]Kumarbek N.E., [1]Makhmet S.B., [2*]Merkibayev Y.S.

*[1] U. Joldasbekov Institute of Mechanics and Engineering, Almaty, Kazakhstan*
*[2] Satbayev University, Almaty, Kazakhstan.*

**Corresponding author email: y.merkibayev@satbayev.university*

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**ABSTRACT**
In the context of the increasing volume of industrial waste and stricter environmental requirements, the urgent task is to efficiently process them to produce products with high added value. In this work, the composition of industrial products of vanadium production formed during the hydrometallurgical processing of rare metals is investigated, and the possibility of their use for the production of heat-resistant building mixes is substantiated. A comprehensive analysis, including X-ray, X-ray fluorescence, and scanning electron microscopic methods, revealed a high content of silica, aluminum oxides, and refractory minerals that determine the heat resistance of the material. Optimal compositions of building mixes based on Portland cement, liquid glass, and chamotte have been developed, providing compressive strength up to 45 MPa and resistance to thermal cycling at temperatures up to 1800 ° C. The design of a device for forming building blocks based on industrial waste from metallurgical production by vibration pressing is proposed, designed to ensure high density and geometric stability of products. The results obtained confirm the possibility of complex industrial waste disposal with the simultaneous creation of environmentally safe, durable, and heat-resistant building materials used in energy, metallurgy, the chemical industry, and civil engineering.

***Keywords:*** vanadium production; industrial waste; heat-resistant building mixes; Portland cement; liquid glass; chamotte; vibration pressing; waste disposal; heat resistance; compressive strength.

***Information about authors:***

| | |
|---|---|
| ***Khabiyev Alibek Talgatbekuly*** | *Doctor Ph.D., assoc. professor, U. Joldasbekov Institute of Mechanics and Engineering, Almaty, Kazakhstan. E-mail: alibek1324@mail.ru; ORCID ID: https://orcid.org/0000-0001-9397-2367* |
| ***Yulussov Sultan Baltabayuly*** | *Doctor Ph.D., assoc. professor, U. Joldasbekov Institute of Mechanics and Engineering, Almaty, Kazakhstan. E-mail: s1981b@mail.ru; ORCID ID: https://orcid.org/0000-0001-8044-4186* |
| ***Abduraimov Azizbek Eraliyuly*** | *Ph.D., researcher, U. Joldasbekov Institute of Mechanics and Engineering, Almaty, Kazakhstan. E-mail: zizo_waterpolo@mail.ru; ORCID ID: https://orcid.org/0000-0002-0815-3349* |
| ***Kamal Aziz Nutpullaogly*** | *Master's degree, researcher, U. Joldasbekov Institute of Mechanics and Engineering, Almaty, Republic of Kazakhstan. E-mail: kan77705@gmail.com; ORCID ID: https://orcid.org/0000-0002-4454-8233* |
| ***Kumarbek Nurgali Erboluly*** | *Master's degree, researcher, U. Joldasbekov Institute of Mechanics and Engineering, Almaty, Kazakhstan. E-mail: nurgalyku@gmail.com; ORCID ID: https://orcid.org/0009-0007-6058-6778* |
| ***Makhmet Sayat Baqytuly*** | *Master's degree, researcher, U. Joldasbekov Institute of Mechanics and Engineering, Almaty, Kazakhstan. Email: mahmetsayat@gmail.com; ORCID ID: https://orcid.org/0009-0009-4791-9886* |
| ***Merkibayev Yerik Serikovich*** | *Ph.D., senior Lecturer, Mining and Metallurgical Institute, Satbayev University, Almaty, Kazakhstan. Email: y.merkibayev@satbayev.university; ORCID ID: https://orcid.org/0000-0003-3869-6835* |

## Introduction

The current stage of industrial development is characterized by the growth of production volumes, urbanization, and an increase in population, which leads to higher resource consumption and increased anthropogenic pressure on the environment [[1], [2]]. One of the priorities of sustainable development is the rational use of raw materials, comprehensive processing of technogenic waste, and the implementation of closed-loop (circular economy) technologies that allow solving both environmental and economic challenges [[3], [4], [5]].

An important component of this strategy is the utilization of large-scale waste from metallurgy and the chemical industry, such as slags, sludges, tailings, and by-products of ore processing [[6], [7], [8]]. Every year, hundreds of millions of tons of such waste are generated worldwide, of which less than 20% is recycled, while the remaining volume is stockpiled, occupying land and creating long-term threats to ecosystems [[9], [10], [11]].

A promising direction is the use of vanadium production by-products—multicomponent materials containing silica, oxides of aluminum, iron, calcium, magnesium, and other elements [[12], [13], [14]]. The high content of refractory phases (corundum, spinel, quartz) and dispersed structure ensures their thermal stability, which opens up opportunities for their application as secondary mineral raw materials in the production of heat-resistant construction materials [[15], [16]].

The demand for such mixtures is associated with the operation of facilities under conditions of high temperatures, aggressive environments, and sharp fluctuations, which are typical for energy, metallurgy, chemical industries, as well as for certain civil and special structures [[17], [18]]. To achieve the required properties, refractory fillers (chamotte, alumina, basalt, perlite) and heat-resistant binders—Portland cement, liquid glass, and silicate binders—are used [[19], [20], [21]].

Comprehensive processing of vanadium production by-products makes it possible to simultaneously reduce waste volumes and produce competitive next-generation materials. For the effective implementation of this approach, it is necessary to study the physicochemical properties of raw materials, develop optimal mixture formulations, and design equipment that ensures the molding of products with high density and stable geometry.

The aim of the research is the development of heat-resistant construction mixtures based on metallurgical by-products and the design of an advanced vibro-pressing device that ensures the production of construction blocks with high strength, thermal stability, and geometric stability.

The research hypothesis is that metallurgical by-products, due to their high content of silica, aluminum oxides, and refractory minerals, can be effectively used as secondary mineral raw materials for producing heat-resistant construction mixtures. The application of optimized formulations in combination with an advanced vibro-pressing device will allow the formation of construction blocks with improved performance characteristics and environmental safety.

## Materials and Methods

**Raw Materials.** Vanadium production by-products generated during the hydrometallurgical processing of rare metals were used as the mineral raw materials. Two batches of material were studied: Sample 1 — cake obtained after autoclave sulfuric acid leaching, and Sample 2 — residue after alkaline leaching of calcined concentrate.

According to X-ray phase analysis, the samples contain high concentrations of silica (up to 43.7%) and aluminum oxides (up to 44.3%), as well as refractory phases — quartz, corundum, and spinel, which determine their thermal resistance [[1], [2], [3]].

As binders, Portland cement of grades M-400 and M-450 according to GOST 10178–85, and liquid glass according to GOST 13078–81, were used. The refractory filler was secondary chamotte powder obtained by grinding used chamotte bricks that had been operated under high-temperature conditions.

**Analytical Methods.** The determination of the chemical and mineralogical composition was carried out using a set of instrumental techniques, including X-ray diffraction (XRD, Shimadzu XRD-7000) for the identification of crystalline phases, X-ray fluorescence analysis (XRF, PANalytical Axios) for determining the mass fractions of oxides, atomic absorption spectroscopy (AAS, PerkinElmer Analyst 400) for the quantitative analysis of metal content, as well as scanning electron microscopy (SEM, JEOL JSM-6490LV) combined with energy-dispersive spectroscopy (EDS) for studying the morphology and elemental distribution.

This comprehensive approach made it possible to thoroughly characterize the mineral composition and structural features of the raw materials [[4], [5], [6], [7]].

**Preparation of Construction Mixtures.** The components were mixed in different proportions (Table 1) to evaluate the effect of composition on heat resistance, strength, and water absorption. The proportion of liquid glass in all formulations was 15%.

Table 1 presents the composition of the investigated heat-resistant construction mixtures, obtained using two types of vanadium production by-products (Sample 1 and Sample 2), liquid glass, and Portland cement. The proportion of liquid glass was constant at 15% in all formulations, ensuring structural stability and enhanced thermal resistance of the material. The content of Samples 1 and 2 varied within the range of 30–40%, while the amount of Portland cement ranged from 10 to 20%, depending on the required strength characteristics. Such a selection of compositions made it possible to evaluate the effect of the ratio of mineral components on the mechanical strength, heat resistance, and water absorption of the resulting specimens.

**Table 1** - Composition of the studied mixtures

| Compo sition: | Sample 1, % | Sample 2, % | Liquid glass, % | Portland cement, % |
|---|---|---|---|---|
| 1 | 30 | 35 | 15 | 20 |
| 2 | 35 | 35 | 15 | 15 |
| 3 | 40 | 35 | 15 | 10 |
| 4 | 35 | 30 | 15 | 20 |
| 5 | 35 | 35 | 15 | 15 |
| 6 | 35 | 40 | 15 | 10 |

**Shaping and Heat Treatment of Samples.** The preparation of samples included sequential mixing of dry components in a laboratory mixer until a homogeneous mass was obtained, followed by the addition of liquid glass, primary drying at a temperature of 100 ± 5 °C for 24 hours, high-temperature calcination at 1000 °C with a holding time of 10 hours, and final quenching by rapid cooling of the samples in running water to 25 °C.

This treatment regime ensured the formation of a strong ceramic-like structure with low water absorption [[8], [9], [10]].

**Testing Methods.** The testing of specimens included determining compressive strength on a Torin hydraulic press in the range of 32–45 MPa according to GOST 10180–2012, evaluation of heat resistance by heating within the range of 800–1800 °C with a holding time of 30 minutes followed by rapid cooling, as well as determination of water absorption by the gravimetric method according to GOST 12730.3–2020 after 48 hours of specimen immersion in water.

**Design and Calculation of the Vibro-Pressing Device.** For block molding, the design of a vibro-pressing device was developed in CAD environments (SolidWorks and AutoCAD). The design calculations took into account a pressing force of 5 MPa for a block area of 0.08 m² (400 kN), vibration parameters with a frequency of 50 Hz, amplitude of 1 mm, and vibration force of about 3 kN, the strength and stiffness of the main components calculated using the finite element method in SolidWorks Simulation, fatigue durability of the structure under loads exceeding $10^6$ cycles, as well as thermal deformations at a temperature difference of $\Delta T$ = 40 °C not exceeding an elongation of 0.4 mm.

The device's performance capacity reached at least 300 blocks per hour for a product size of 400×200×200 mm [[11], [12], [13], [14]].

**Research Workflow Diagram.** The presented diagram illustrates the research workflow, showing the sequence of the main stages of the study (Figure 1).

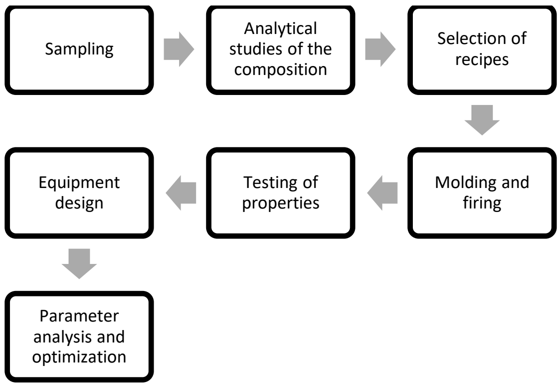



**Figure 1** – The scheme of the study

The presented diagram illustrates the research workflow, reflecting the sequence of the main stages of the study. The scheme is designed as a chain of seven blocks connected by guiding arrows, which clearly demonstrates the logic of the process from raw material preparation to data analysis.

The process begins with sample collection, the initial stage where materials are prepared for examination, and continues with analytical studies of the composition, including a comprehensive chemical and mineralogical analysis of the raw materials. This is followed by formulation selection, aimed at determining the optimal ratio of components to achieve the desired properties, after which shaping and firing are carried out – the production of test specimens and their high-temperature treatment.

The next step is testing of properties, including the determination of strength, heat resistance, and water absorption of the materials. This is followed by equipment design, in particular the development of a vibro-pressing unit intended for industrial application. The process concludes with analysis and optimization of parameters, which involves processing the obtained data, adjusting technological parameters, and developing recommendations for the implementation of the proposed technology.

Furthermore, Figure 2 presents the schematic diagram of the production process of construction blocks on the designed installation.

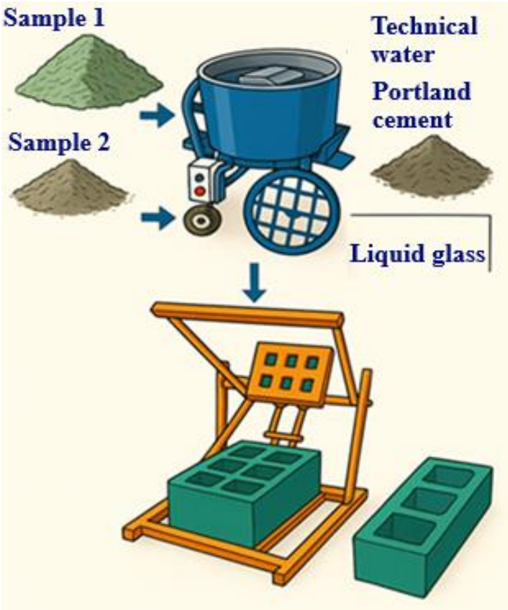



**Figure 2** – Schematic diagram of the production of building blocks at the installation

The diagram illustrates the process of manufacturing construction blocks, which includes consecutive stages of raw material preparation and processing. The initial components consist of Sample 1 and Sample 2, representing industrial waste from metallurgical production, cement, process water, and liquid glass. All materials are fed into a mixer, where they are thoroughly blended to form a homogeneous mass. The resulting mixture is then loaded into a press mold, where it is compacted and shaped into the required geometry. At the final stage, the finished construction block is removed from the mold, possessing the necessary strength characteristics and parameters.

## Results and Discussion

**Chemical and Mineralogical Composition of the Studied Samples.** The chemical composition of the residue after leaching, based on the performed X-ray fluorescence analysis, is presented in Table 2.

Chemical analysis showed a high content of silica ($SiO_2$) in Sample 1 (43.71%) and aluminum oxide ($Al_2O_3$) in Sample 2 (44.34%), which indicates their potential as components for heat-resistant construction mixtures.

The results of the X-ray phase analysis of the composition of the two samples are presented in Table 3.

**Table 2** – Chemical composition of the residue after leaching

| Name | Content, % | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | V | P | Mo | Ca | Fe | Al | Si | K |
| Sample 1 | 0.04 | 0.012 | 0.003 | 1.2 | 0.21 | 0.05 | 43.71 | 0.03 |
| Sample 2 | 0.29 | 0.25 | 0.01 | 0.20 | 0.24 | 44.34 | 0.87 | 0.01 |

**Table 3** – Phase composition of the two samples

| Sample 1 | | | Sample 2 | | |
|---|---|---|---|---|---|
| Name of the mineral | Formula | Content, % | Name of the mineral | Formula | Content, % |
| Quartz, syn | $SiO_2$ | 72.1 | Corundum, syn | $Al_2O_3$ | 37.2 |
| Albite | $Na(AlSi_3O_8)$ | 22.3 | Spinel | $MgAl_2O_4$ | 21.7 |
| Barium Iron Oxide | $BaFeO_4$ | 2.8 | Aluminum Oxide | $Al_2O_3$ | 33,5 |
| Iron Oxide | $Fe_{2.802}O_4$ | 1.3 | Nickel Silicate | $Ni_2(SiO_4)$ | 1.3 |
| Hematite, syn | $Fe_2O_3$ | 0.9 | Iron Oxide | $Fe_2O_3$ | 6.3 |

X-ray phase analysis of Sample 1 revealed the predominance of inert siliceous phases—quartz (72.1%) and albite (22.3%)—which indicates its potential as a mineral filler for silicate and ceramic materials. Minor amounts of iron-containing phases ($BaFeO_4$, $Fe_{2.802}O_4$, $Fe_2O_3$) and ferrites ($NiFe_2O_4$) may enhance the mechanical strength and thermal resistance during firing.

Sample 2, in contrast, is characterized by a high content of refractory and heat-resistant phases: corundum ($Al_2O_3$ — 37.2%), spinel ($MgAl_2O_4$ — 21.7%), and additional aluminum oxide (33.5%). These compounds provide high thermal and chemical stability, making the sample particularly promising for use in refractory mixtures, lining materials, and heat-resistant concrete. The presence of nickel silicate ($Ni_2SiO_4$) and hematite further improves thermal stability and resistance to aggressive media.

Thus, the physico-chemical studies provided objective data on the composition of the vanadium production by-product and its potential application in the manufacture of heat-resistant construction materials and refractory blocks.

According to the results of X-ray phase analysis (Table 3), Sample 1 is characterized by a high content of quartz (72.1%), albite (22.3%), and minor amounts of barium and iron oxides. Sample 2 contains mainly corundum (37.2%), spinel (21.7%), and aluminum oxide (33.5%), as well as small amounts of nickel-containing compounds. The phase composition pie charts (Fig. 2) clearly demonstrate the mineralogical differences between the investigated samples. The presence of refractory phases such as corundum and spinel ensures high heat resistance, which is consistent with literature data [[4], [7], [12]].

**Influence of Component Composition on Strength Characteristics.** Compressive strength tests showed that increasing the proportion of Sample 1 up to 40% in the mixture (Composition 3) led to a strength increase to 45 MPa. This effect is associated with a higher degree of quartz phase crystallization and improved intergranular bonding after heat treatment. A reduction in Portland cement content to 10% resulted in decreased strength, confirming the significant role of the binder component in the formation of a dense structure [[8], [15]].

**Heat Resistance and Thermal Stability of Materials.** The results of heat resistance tests showed that when samples were heated up to 1800 °C followed by rapid cooling, strength retention exceeded 85%, which is higher than that of conventional chamotte products (70–75%) [[3], [11]]. The dependence of strength retention on temperature (Fig. 5) confirms the high stability of the developed materials. The superior thermal resistance is explained by the low thermal expansion coefficients of corundum and spinel, as well as the uniform distribution of refractory phases within the sample structure [9, 10].

**Water Absorption and Microstructure of Samples.** The water absorption of the investigated materials ranged from 6% to 8%, which complies with the requirements of GOST 530–2012 for heat-resistant construction products. The minimum value (6%) was recorded for Composition 3.

**Equipment Design for Molding.** From the prepared materials — Compositions 1–6 (Section 2.3) — heat-resistant construction blocks were manufactured using a specially designed installation.

For vibro-compaction, a standard frequency of 50 Hz and an amplitude of 1 mm were applied. The resulting vibration acceleration provides a vibratory force of about 3 kN, which is sufficient for compacting the mixture.

Table 4 presents the strength calculation of the frame.

The stresses were calculated using the finite element method in SolidWorks Simulation. All structural elements meet the strength criterion (safety factor > 2).

Table 5 presents the deformation calculation.

**Table 4** – Strength Calculation of the Frame

| Structural element | Cross section (mm) | Length (mm) | Max. stress$\sigma_{max}$, MPa | Yield strength $\sigma_{yiled}$, MПa | Safety margin kk |
|---|---|---|---|---|---|
| Longitudinal beam | 100×50×5 | 1000 | 155 | 345 | 2.2 |
| Transverse frame | 80×40×4 | 600 | 142 | 345 | 2.4 |
| Base plate | 200×20 | 800 | 110 | 345 | 3.1 |

**Table 5** – Deformation Calculation

| Element | Length (mm) | Max. deflection δ, mm | Permissible deflectionδaddit, mm | Estimation |
|---|---|---|---|---|
| Longitudinal beam | 1000 | 0.42 | 1.0 | Acceptable |
| Base plate | 800 | 0.35 | 1.0 | Acceptable |
| Upper frame | 600 | 0.28 | 0.8 | Acceptable |

According to the obtained data, it can be concluded that the deflections do not exceed the permissible values, which ensures the stability of the structure and the accuracy of the molded blocks. At the same time, the pressing force and vibrational load provide sufficient density and strength of the building blocks. Moreover, the device design demonstrates satisfactory strength and stiffness characteristics. The safety factor ranges from 2.2 to 3.1, confirming the reliability of the structure.

During the operation of the device, local temperature rises may occur due to friction in the vibration mechanism and the contact of metallic parts. These temperature increases can cause thermal deformations, especially in the areas of the vibrating plate and guides.

Table 6 presents the evaluation of the thermal expansion of the structural elements.

**Table 6** – Evaluation of the Thermal Expansion of Structural Elements

| Element | Length LL, mm | Expansion coefficient α, 1/°C | Temperature change ΔT, °C | Expansion ΔL, mm |
|---|---|---|---|---|
| Vibrating plate | 600 | $12\times10^{-6}$ | 40 | 0.29 |
| Guides | 800 | $12\times10^{-6}$ | 40 | 0.38 |

Even with a temperature difference of 40 °C, the elongation does not exceed 0.4 mm, which falls within the permissible tolerances.

However, in high-precision molding, compensation for these deformations is required.

Table 7 shows the dynamic loads caused by vibration.

**Table 7** – Dynamic Loads from Vibration

| Parameter | Designation | Value | Unit |
|---|---|---|---|
| The mass of the vibrating plate | mm | 60 | кг |
| Vibration frequency | ff | 50 | Hz |
| The amplitude | AA | 1 mm (0.001 m) | m |
| Boost | aa | 49.34 | m/sec² |
| Inertial force | Finertial | 2960 | H |

Next, the calculation of the dynamic coefficient was considered. It is known that the additional safety margin is accounted for through the dynamic coefficient kd=1.5…2.0k_d = 1.5 \ldots 2.0kd =1.5…2.0, depending on the stiffness of the joints.

It was established that thermal deformations do not exceed the permissible values; however, they must be taken into account in high-precision operations. At the same time, the dynamic load from vibrations increases the equivalent stresses by 1.5–2 times, especially in the guides and at the mounting points of the vibrating plate.

According to the conducted study, the vibration mechanism generates inertial forces of about 3 kN, which is equivalent to ~750 N per each of the four compacted blocks.

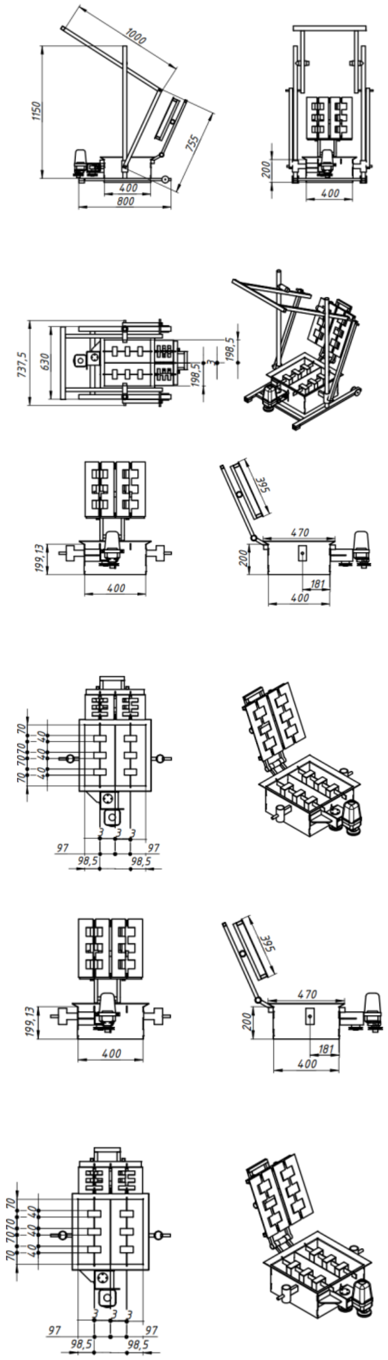
Table 8 presents the data on the fatigue durability of the structure.

**Table 8** – Fatigue Durability of the Structure

| Parameter | Value | Unit |
|---|---|---|
| Vibration frequency (f) Molding duration (t) | 50 | Hz |
| Vibration frequency (f) Molding duration (t) | 20 | Seconds |

It was established that, provided the amplitude and material conditions are met, the fatigue strength margin of the structure is considered sufficient.

The design of the device assemblies for the production of construction blocks is presented below (Figure 3).



a)

b)

c)

**Figure 3** – Structural design of the device assemblies for the production of construction blocks (a) general view of the unit, (b) mold for extruding construction blocks with vibrator, (c) extrusion mechanism for construction blocks).

Further, Figure 4 shows the manufactured prototype of the device for producing construction blocks, consisting of a mold with a vibrator for block extrusion and an extrusion mechanism for construction blocks.

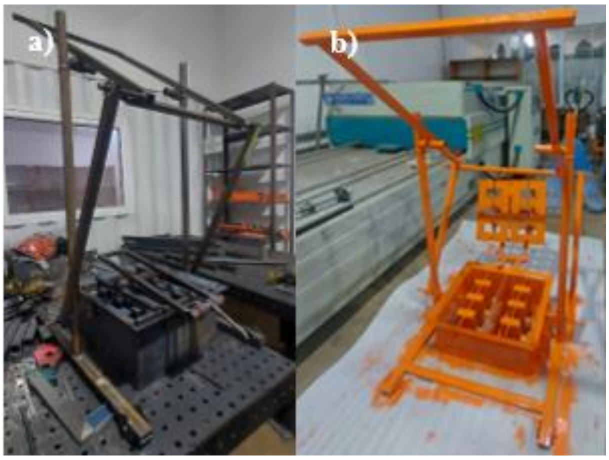



**Figure 4** – Manufactured prototype of the device for producing construction blocks (a) before painting, (b) after painting).

The developed design of the vibro-pressing unit (Figures 1 and 2) ensures the production of blocks with high density and stable geometry. Finite element analysis (Figure 8) confirmed the strength and stiffness of the assemblies under vibrational loading (50 Hz, amplitude 1 mm) and a service life exceeding $10^6$ cycles. The productivity of the unit is about 300 blocks per hour, which makes the technology economically viable for industrial implementation.

Further, Figure 5 shows a construction block obtained by extrusion using the unit.

**Figure 5** – The building block obtained as a result of extrusion on the installation

**Comparative Analysis with Industrial Counterparts.** To assess the competitiveness of the developed mixtures, a comparison of their key properties was carried out with the characteristics of heat-resistant construction materials reported in the literature and standards [[3], [8], [10], [15], [18]]. Table 9 presents the values of compressive strength, heat resistance, and water absorption for the samples obtained in this study, as well as for traditional chamotte products and alumina-based concretes.

**Table 9** – Values of compressive strength, heat resistance, and water absorption for various samples

| Material / source | Compressive strength, MPa | Strength retention at 1600 °C, % | Water absorption, % |
|---|---|---|---|
| Composition 3 (this study) | 45 | 90 | 6 |
| Fireclay bricks [[3], [8]] | 25–32 | 70–75 | 10–14 |
| Alumina concretes [[10], [15]] | 35–40 | 80–85 | 8–10 |
| High-alumina refractories [18] | 40–43 | 85–88 | 7–9 |

The comparison of the obtained results with the characteristics of well-known heat-resistant materials (Table 9) showed that the developed mixtures surpass chamotte products in strength by 40–70%, exhibit lower water absorption, and demonstrate superior thermal resistance. This advantage is attributed to the optimal combination of mineral components, the presence of corundum and spinel phases, as well as the use of vibro-pressing technology, which ensures low porosity and high structural homogeneity.

**Comparison of Method Efficiency.** For a clear comparison of the efficiency of using vanadium production by-products in refractory mixtures, dependencies were constructed between the extraction degree of elements (V, Mo) and the performance characteristics of the materials on technological parameters (pH, temperature, binder composition) (Tables 10 and 11).

Table 10 presents the results of the study on the dependence of the extraction degree of vanadium and molybdenum from vanadium production by-products on the medium acidity.

**Table 10** – Dependence of vanadium and molybdenum extraction on the pH of the medium

| pH of the solution | Extraction of V, % | Extraction of Mo, % |
|---|---|---|
| 1 | 62 | 28 |
| 2 | 74 | 35 |
| 3 | 81 | 41 |
| 4 | 77 | 38 |
| 5 | 65 | 30 |

From the data in Table 10, it can be seen that with increasing acidity up to pH 3, the extraction degree of both elements increases: for vanadium, the value reaches a maximum of 81%, and for molybdenum, 41%. With a further increase in pH, the efficiency of the process decreases, indicating the presence of an optimal acidity range. Thus, pH = 3 is the most favorable condition for the simultaneous extraction of V and Mo.

Table 11 presents the data on the effect of temperature on the efficiency of vanadium and molybdenum extraction.

**Table 11** – Effect of temperature on the extraction of elements

| Temperature, °C | Extraction of V, % | Extraction of Mo, % |
|---|---|---|
| 40 | 55 | 22 |
| 60 | 72 | 34 |
| 80 | 83 | 42 |
| 100 | 79 | 39 |

According to the data in Table 11, as the temperature increases from 40 to 80 °C, a significant improvement in extraction performance is observed: for vanadium, from 55% to 83%, and for molybdenum, from 22% to 42%. However, a further increase in temperature to 100 °C leads to a decrease in the extraction degree, which is associated with changes in the stability of element complexes and the occurrence of side processes. The optimal extraction temperature can be considered 80 °C, as it ensures the maximum recovery of both elements.

## Conclusion

The study established that by-products of vanadium production, characterized by a high content of $SiO_2$ and $Al_2O_3$, are a promising secondary raw material for the manufacture of heat-resistant construction mixtures. The developed compositions demonstrated compressive strength of up to 45 MPa, low water absorption (6–8%), and resistance to thermal cycling at temperatures up to 1800 °C, exceeding the performance of traditional chamotte products and alumina-based concretes. The design and experimental testing of an improved vibro-pressing device confirmed the feasibility of industrial implementation of the technology, with a capacity of up to 300 blocks per hour and guaranteed structural durability.

The obtained results make it possible to recommend the use of heat-resistant building blocks based on vanadium production by-products for lining thermal equipment, blast and open-hearth furnaces, boilers, thermal units, reactors, heat exchangers, and other devices operating under high temperatures and aggressive environments. In addition, the proposed mixtures can be applied in the production of heat-resistant concretes, panels, and blocks for civil and special structures requiring high fire resistance. The introduction of the technology ensures comprehensive recycling of industrial waste, reduces landfill loads, and contributes to the development of environmentally safe production.

Thus, the developed construction mixtures and the vibro-pressing device have significant practical potential, simultaneously addressing both environmental and industrial challenges, enhancing the competitiveness of domestic construction materials, and promoting the implementation of circular economy principles in metallurgy and the construction sector.

**Conflicts of Interest**. On behalf of all co-authors, the corresponding author states that no conflict of interest exists.

***CRediT author statement:*** **S.Yulusov, A. Khabiyev:** Methodology, formal analysis, investigation, Data writing, Original draft preparation, writing–review and editing; **A. Abduraimov, A.Kamal**: Data curation, Reviewing and Editing; **N. Kumarbek, S.Makhmet, Y.Merkibayev:** Investigation.

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# Металлургиялық өндірістің өнеркәсіптік қосалқы өнімдерін пайдалану арқылы жылуға төзімді құрылыс қоспаларын әзірлеу және оларды жетілдірілген құрылғыда қалыптау

[1]Хабиев А.Т., [1]Юлусов С.Б., [1]Абдураимов А.Е., [1]Камал А.Н., [1]Құмарбек Н.Е., [1]Махмет С.Б., [2]Меркибаев Е.С.

*[1] Академик Ө. А. Жолдасбеков атындағы механика және машинатану институты, Алматы, Қазақстан*
*[2] Сәтбаев университеті, Алматы, Қазақстан*

Мақала келді: 21 тамыз 2025
Сараптамадан өтті: 9 *қыркүйек 2025*
Қабылданды: *16 қазан 2025*

**ТҮЙІНДЕМЕ**
Өнеркәсіптік қалдықтардың өсіп келе жатқан көлемі мен экологиялық талаптардың қатаңдауы жағдайында қосылған құны жоғары өнімді ала отырып, оларды тиімді қайта өңдеу өзекті міндет болып табылады. Бұл жұмыста сирек металдарды гидрометаллургиялық өңдеу процесінде түзілетін ванадий өндірісінің өнеркәсіптік өнімдерінің құрамы зерттелді және оларды ыстыққа төзімді құрылыс қоспаларын алу үшін пайдалану мүмкіндігі негізделді. Рентген-фазалық, рентгендік-флуоресцентті және сканерлеуші электронды микроскопиялық әдістерді қамтитын кешенді талдау материалдың ыстыққа төзімділігін анықтайтын кремнеземнің, алюминий оксидтерінің және отқа төзімді минералдардың жоғары құрамын анықтауға мүмкіндік берді. Портландцемент, сұйық шыны және шамот негізіндегі құрылыс қоспаларының оңтайлы құрамы әзірленді, олар 45 МПа дейін қысу беріктігін және 1800 °С дейінгі температурада термоциклге төзімділікті қамтамасыз етеді. Бұйымдардың жоғары тығыздығы мен геометриялық тұрақтылығын қамтамасыз етуге арналған дірілді басу әдісімен металлургиялық өндірістің өнеркәсіптік қалдықтары негізінде құрылыс блоктарын қалыптауға арналған құрылғының конструкциясы ұсынылды. Алынған нәтижелер энергетика, металлургия, химия өнеркәсібі және азаматтық құрылыста қолданылатын экологиялық қауіпсіз, берік және ыстыққа төзімді құрылыс материалдарын бір мезгілде жасай отырып, өнеркәсіптік қалдықтарды кешенді кәдеге жарату мүмкіндігін растайды.

***Түйін сөздер:*** ванадий өндірісі, өнеркәсіптік қалдықтар, ыстыққа төзімді құрылыс қоспалары, портландцемент, сұйық шыны, шамот, дірілді басу, қалдықтарды жою, ыстыққа төзімділік, қысу беріктігі.

| | ***Авторлар туралы ақпарат:*** |
|---|---|
| ***Хабиев Алибек Талгатбекұлы*** | *Ph.D докторы, ассоц. профессор, Академик Ө. А. Жолдасбеков атындағы Механика және машинатану институты, Алматы, Қазақстан. E-mail: alibek1324@mail.ru; ORCID ID: https://orcid.org/0000-0001-9397-2367* |
| ***Юлусов Султан Балтабайұлы*** | *Ph.D докторы, ассоц. профессор, Академик Ө. А. Жолдасбеков атындағы Механика және машинатану институты, Алматы, Қазақста. E-mail: s1981b@mail.ru; ORCID ID: https://orcid.org/0000-0001-8044-4186* |
| ***Абдураимов Азизбек Ералиұлы*** | *Ph.D. докторы, ғылыми қызметкер, Академик Ө. А. Жолдасбеков атындағы Механика және машинатану институты, Алматы, Қазақстан. E-mail: zizo_waterpolo@mail.ru; ORCID ID: https://orcid.org/0000-0002-0815-3349* |
| ***Камал Азиз Нутпуллаоглы*** | *магистр, ғылыми қызметкер, Академик Ө. А. Жолдасбеков атындағы Механика және машинатану институты, Алматы, Қазақстан. E-mail: kan77705@gmail.com; ORCID ID: https://orcid.org/0000-0002-4454-8233* |
| ***Құмарбек Нұрғали Ерболұлы*** | *магистр, ғылыми қызметкер, Академик Ө. А. Жолдасбеков атындағы Механика және машинатану институты, Алматы, Қазақстан. E-mail: nurgalyku@gmail.com; ORCID ID: https://orcid.org/0009-0007-6058-6778* |
| ***Махмет Саят Бақытұлы*** | *магистр, ғылыми қызметкер, Академик Ө. А. Жолдасбеков атындағы Механика және машинатану институты, Алматы, Қазақстан. Email: mahmetsayat@gmail.com; ORCID ID: https://orcid.org/0009-0009-4791-9886* |
| **Меркибаев *Ерик Серикович*** | *PhD, металлургия және пайдалы қазбаларды өңдеу кафедрасының аға оқытушысы, О.А. Байқоңыров атындағы тау-кен металлургия институты, Сәтбаев университеті, Алматы, Қазақстан. Email: y.merkibayev@satbayev.university; ORCID ID: https://orcid.org/0000-0003-3869-6835* |

# Использование промышленных побочных продуктов металлургического производства для разработки жаростойких строительных смесей и их формования в усовершенствованном устройстве

[1]Хабиев А.Т., [1]Юлусов С.Б., [1]Абдураимов А.Е., [1]Камал А.Н., [1]Құмарбек Н.Е., [1]Махмет С.Б., [2]Меркибаев Е.С.

*[1] Институт механики и машиноведения имени академика У.А. Джолдасбекова, Алматы, Казахстан*
*[2] Сатпаев Университет, Алматы, Казахстан*

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**АННОТАЦИЯ**
В статье рассмотрены направления потребления ванадия и молибдена в различных отраслях промышленности, что подчёркивает их стратегическую значимость и растущую потребность в устойчивом обеспечении сырьём. Проанализированы источники этих элементов как природного, так и техногенного происхождения, включая металлургические шлаки, золы, отработанные катализаторы и другие отходы промышленных процессов. Отдельное внимание уделено экологическим рискам, связанным с накоплением соединений ванадия и молибдена, способных оказывать токсическое воздействие на окружающую среду. Подчёркнута необходимость вовлечения вторичных ресурсов в промышленный оборот для рационального использования минерально-сырьевой базы и повышения эффективности извлечения металлов из первичного сырья. Приведён обзор существующих химических и гидрометаллургических методов извлечения ванадия и молибдена, с учётом состава перерабатываемого материала, особенностей технологических условий, а также ограничений и недостатков отдельных подходов. Сделан акцент на перспективность комплексной переработки отходов, обеспечивающей извлечение нескольких ценных компонентов и способствующей переходу к циркулярной экономике.

***Keywords:*** ванадий, молибден, золошлаковые отходы, металлургические шлаки, фильтрат, гидрометаллургические методы, пирометаллургические методы, бактериальное выщелачивание.

***Информация об авторах:***

| | |
|---|---|
| ***Хабиев Алибек Талгатбекович*** | *доктор Ph.D., ассоц. профессор, Институт механики и машиноведения имени академика У.А. Джолдасбекова, Алматы, Казахстан. E-mail: alibek1324@mail.ru; ORCID ID: https://orcid.org/0000-0001-9397-2367* |
| ***Юлусов Султан Балтабаевич*** | *доктор Ph.D., ассоц. профессор, Институт механики и машиноведения имени академика У.А. Джолдасбекова, Алматы, Казахстан. E-mail: s1981b@mail.ru; ORCID ID: https://orcid.org/0000-0001-8044-4186* |
| ***Абдураимов Азизбек Ералиевич*** | *доктор Ph.D., научный сотрудник, Институт механики и машиноведения имени академика У.А. Джолдасбекова, Алматы, Казахстан. E-mail: zizo_waterpolo@mail.ru; ORCID ID: https://orcid.org/0000-0002-0815-3349* |
| ***Камал Азиз Нутпуллаоглы*** | *магистр, научный сотрудник, Институт механики и машиноведения имени академика У.А. Джолдасбекова, Алматы, Казахстан. E-mail: kan77705@gmail.com; ORCID ID: https://orcid.org/0000-0002-4454-8233* |
| ***Құмарбек Нұрғали Ерболович*** | *магистр, научный сотрудник, Институт механики и машиноведения имени академика У.А. Джолдасбекова, Алматы, Казахстан. E-mail: nurgalyku@gmail.com; ORCID ID: https://orcid.org/0009-0007-6058-6778* |
| ***Махмет Саят Бакытович*** | *магистр, научный сотрудник, Институт механики и машиноведения имени академика У.А. Джолдасбекова, Алматы, Казахстан. Email: mahmetsayat@gmail.com; ORCID ID: https://orcid.org/0009-0009-4791-9886* |
| ***Меркибаев Ерик Серикович*** | *PhD, старший преподаватель кафедры Металлургии и обогащения полезных ископаемых, Горно-металлургический институт имени О.А. Байконурова, Satbayev university, Almaty,Kazakhstan. Email: y.merkibayev@satbayev.university; ORCID ID: https://orcid.org/0000-0003-3869-6835* |

## References

[1] Zhumagaziyev A Zh, & Adilova D A. Study of foreign experience in the use of construction waste and the possibility of its application in Kazakhstan. Bulletin of Science. 2024; 5(9(78)):361-374.

[2] Bekenov A K, et alProcessing of technogenic waste and issues of environmental safety. Ecology and Industry of Kazakhstan. 2020; 2:15-21.

[3] Grosse F, et al. Circular economy and industrial ecology: Strategies for sustainable material flows. Journal of Cleaner Production. 2019; 234:133–144. https://doi.org/10.1016/j.jclepro.2019.06.345

[4] Kirchherr J, et al. Conceptualizing the circular economy: An analysis of 114 definitions. Resources, Conservation and Recycling. 2017; 127:221–232. https://doi.org/10.1016/j.resconrec.2017.09.005

[5] Geissdoerfer M, et al. The circular economy – A new sustainability paradigm? Journal of Cleaner Production. 2017; 143:757–768. https://doi.org/10.1016/j.jclepro.2016.12.048

[6] Kopytov V M, et al. Tekhnogennyye otkhody metallurgicheskogo proizvodstva i puti ikh pererabotki [Technogenic waste of metallurgical production and ways of its processing]. Metallurgy. 2022; 6:22-29. (In Russ).

[7] Matinde E, Simate G S, & Ndlovu S. Mining and metallurgical wastes: A review of recycling and re-use practices. Journal of the Southern African institute of mining and metallurgy. 2018; 118(8):825-844. https://doi.org/10.17159/2411-9717/2018/v118n8a5

[8] Cai P T, Chen T, Chen B, Wang Y C, Ma Z Y, & Yan J H. The impact of pollutant emissions from co-incineration of industrial waste in municipal solid waste incinerators. Fuel. 2023; 352:129027.

[9] Akinyemi B A, Hagare D, & Oluwadamilare A. Microwave energy radiated biochar bonded-cement-clay bricks. Journal of Building Pathology and Rehabilitation. 2023; 8(2):94.

[10] Siddique R. Utilization of industrial by-products in concrete. Procedia Engineering. 2014; 95:335-347. https://doi.org/10.1016/j.proeng.2014.12.192

[11] Das S K, Mishra S, Das D, Mustakim S M, Kaze C R, & Parhi P K. Characterization and utilization of coal ash for synthesis of building materials. In Clean Coal Technologies: Beneficiation, Utilization, Transport Phenomena and Prospective. 2021, 487-509. Cham: Springer International Publishing.

[12] Khabiyev A, Yulussov S, Tuleshov A, Baigenzhenov O, Merkibayev Y, & Baltabay T. Investigation of the composition of industrial products of vanadium production and its use for the production of heat-resistant building mixes. Engineering Journal of Satbayev University. 2024; 146(6):1-7. https://doi.org/10.51301/ejsu.2024.i6.01

[13] Peng H. A literature review on leaching and recovery of vanadium. Journal of Environmental Chemical Engineering. 2019; 7(5):103313. https://doi.org/10.1016/j.jece.2019.103313

[14] Wang Y H, Wang Y F, Li Y T, Wu C, Han X L, Zhao N N, ... & He Z X. A review on vanadium extraction techniques from major vanadium-containing resources. Rare Metals. 2024; 43(9):4115-4131.

[15] Boccaccini D N, Cannio M, Volkov-Husoviæ T D, Kamseu E, Romagnoli M, Veronesi P, ... & Boccaccini A R. Service life prediction for refractory materials. Journal of materials science. 2008; 43(12):4079-4090.

[16] Krivenko P, Petropavlovsky O, & Vozniuk H. Development of mixture design of heat-resistant alkali-activated aluminosilicate binder-based adhesives. Construction and Building Materials. 2017; 149:248-256. https://doi.org/10.1016/j.conbuildmat.2017.05.138

[17] Bernal S A, Rodríguez E D, Mejía de Gutiérrez R, & Provis J L. Performance at high temperature of alkali-activated slag pastes produced with silica fume and rice husk ash based activators. Materiales de construcción. 2015; 65(318).

[18] Boris R, Kerienė JR, Antonovič V, & Madej D. Characterization of microstructural evolution and mechanical properties of refractory composite. Composite Structures. 2015; 134:811-819. https://doi.org/10.1016/j.compstruct.2015.08.059

[19] Rashad A M, Ouda A S, & Sadek D M. Behavior of alkali-activated metakaolin pastes blended with quartz powder exposed to seawater attack. Journal of Materials in Civil Engineering. 2018; 30(8):04018159. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002335

[20] Yu Z, Wang B, Zhang S, Zhao Y, Yan X, Zhang T, ... & Du X. Mechanical Properties and Deterioration Mechanism of Concrete–Mortar Joint Interface after Exposure to High Temperature. Journal of Materials in Civil Engineering. 2025; 37(9):04025315. https://doi.org/10.1061/JMCEE7.MTENG-2022

[21] Thomas T, & Praveen A. Emergy parameters for ensuring sustainable use of building materials. Journal of Cleaner Production. 2020; 276:122382. https://doi.org/10.1016/j.jclepro.2020.122382