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RESEARCH ARTICLE

INVESTIGATION OF THE COMPOSITION OF ASH AND SLAG WASTE FROM THERMAL POWER PLANTS FOR USE IN BUILDING CERAMICS

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Abstract. *In the context of intensified housing construction and the transition to a "green" economy in the Republic of Kazakhstan, the demand for energy-efficient and environmentally friendly building materials is increasing. Against the backdrop of a shortage of high-quality clay raw materials, the use of ash and slag waste (ASW) from thermal power plants in the production of construction ceramics is becoming especially relevant. Chemical and phase analysis of ash and slag from Pavlodar TPP-3 and natural clay from the Pavlodar deposit has been made in the study. X-ray fluorescence analysis (XRF) and X-ray diffraction (XRD) methods have been applied using Bruker equipment. The data obtained have been interpreted according to current international standards. Ash and slag materials contain up to 61.19% SiO_2 and 18.61% Al_2O_3, as well as significant amounts of fluxing oxides (CaO, MgO, K_2O), which help reduce sintering temperature. The clay is characterized by high Al_2O_3 and Fe_2O_3 content, which makes it suitable for the production of red-fired ceramic products. X-ray fluorescence analysis confirmed the presence of such phases as quartz, mullite, and anorthite in the ash and slag, and kaolinite, illite, and feldspars in the clay. An integrated approach to combining ash and slag with clay allows to optimize the ceramic mass formulation, improving its plasticity and strength. The use of ash and slag waste in construction ceramics ensures technological efficiency and solves environmental problems by reducing industrial waste volumes, expanding the raw material base, increasing production profitability, and supporting sustainable development.*

Keywords: *Ash and slag, construction ceramics, phase composition, aluminosilicates, fluxing additives, heat resistance.*

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ҒЫЛЫМИ МАҚАЛА

ҚҰРЫЛЫС КЕРАМИКАСЫНДА ҚОЛДАНУҒА АРНАЛҒАН ЖЭО КҮЛ ҚОЖ ҚАЛДЫҚТАРЫНЫҢ ҚҰРАМЫН ЗЕРТТЕУ

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Аңдатпа. *Тұрғын үй құрылысының қарқындылығы және «жасыл» экономикаға көшу жағдайында Қазақстан Республикасында энергиялық тиімді және экологиялық таза құрылыс материалдарына қажеттілік артып келеді. Кондициялық саз шикізаты тапшы болғандықтан, құрылыс керамикасын өндіруде жылу электр орталығының (ЖЭО) күл-қож қалдықтарын (ҚҚҚ) пайдалану ерекше өзекті болып отыр. Зерттеу барысында Павлодар ЖЭО-3 күл қождары мен Павлодар кен орнының табиғи сазына химиялық және фазалық талдау жүргізілді. Bruker жабдығын қолдана отырып, рентгендік флуоросцентті талдау (РФТ) және рентгендік дифракция (РД) әдістері қолданылды. Талдау деректері қолданыстағы халықаралық стандарттарға сәйкес түсіндірілді. Күл қож құрамында 61,19% дейін SiO_2 және 18,61% Al_2O_3, сондай-ақ күйдіру температурасының төмендеуіне ықпал ететін флюс оксидтерінің (CaO, MgO, K_2O) айтарлықтай мөлшері бар. Саз Al_2O_3 және Fe_2O_3 құрамының жоғарылауымен сипатталады, бұл оның қызыл жанғыш керамикалық бұйымдарды өндіруге жарамдылығын қамтамасыз етеді. Рентгендік флуоросцентті талдау күл қожындағы кварц, муллит және анортит, саздағы каолинит, иллит, дала шпаттары сияқты фазалардың болуын растады. Күл қождары мен сазды біріктірудің кешенді тәсілі керамикалық массаның рецептурасын оңтайландыруға, икемділік пен беріктікті жақсартуға. Құрылыс керамикасында ҚҚҚ-ын қолдану технологиялық тиімділікті қамтамасыз етіп қана қоймай, сонымен қатар техногендік қалдықтардың көлемін азайтып, шикізат базасын кеңейту, өндіріс табыстылығын арттыру және тұрақты даму тұжырымдамасын қолдай отырып, экологиялық міндеттерді шешеді.*

Түйін сөздер: *Күл-қож, құрылыс керамикасы, фазалық құрам, алюминий силикаттары, флюс қоспалары, ыстыққа төзімділік*

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НАУЧНАЯ СТАТЬЯ

ИССЛЕДОВАНИЕ СОСТАВА ЗОЛОШЛАКОВЫХ ОТХОДОВ ТЭЦ ДЛЯ ПРИМЕНЕНИЯ В СТРОИТЕЛЬНОЙ КЕРАМИКЕ

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Аннотация. *В условиях интенсификации жилищного строительства и перехода к «зёленой» экономике в Республике Казахстан возрастает потребность в энергоэффективных и экологичных строительных материалах. На фоне дефицита кондиционного глинистого сырья особую актуальность приобретает использование золошлаковых отходов (ЗШО) ТЭЦ в производстве строительной керамики. В исследовании проведен химический и фазовый анализ золошлаков Павлодарской ТЭЦ-3 и природной глины Павлодарского месторождения. Применены методы рентгенофлуоросцентного анализа (РФА) и рентгеновской дифракции (РД) с использованием оборудования Bruker. Данные анализов интерпретированы в соответствии с действующими международными стандартами. Золошлаки содержат до 61,19 % SiO_2 и 18,61 % Al_2O_3, а также значительные количества флюсующих оксидов (CaO, MgO, K_2O), способствующих снижению температуры спекания. Глина характеризуется повышенным содержанием Al_2O_3 и Fe_2O_3, что обеспечивает ее пригодность для производства красножгущихся керамических изделий. Рентгенофлуоросцентный анализ подтвердил наличие таких фаз, как кварц, муллит и анортит в золошлаке, и каолинит, иллит, полевые шпаты в глине. Комплексный подход к сочетанию золошлаков и глины позволяет оптимизировать рецептуру керамической массы, улучшить пластичность и прочность. Применение золошлаковых отходов в строительной керамике обеспечивает не только технологическую эффективность, но и решает экологические задачи, снижая объемы техногенных отходов, расширяя сырьевую базу, повышая рентабельность производства и поддерживая концепцию устойчивого развития.*

Ключевые слова:. *Золошлаки, строительная керамика, фазовый состав, алюмосиликаты, флюсующие добавки, термостойкость.*

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CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

АЛҒЫС / ҚАРЖЫЛАНДЫРУ КӨЗІ

Зерттеу жеке қаржыландыру көздерін пайдалана отырып жүргізілді.

МҮДДЕЛЕР ҚАҚТЫҒЫСЫ

Авторлар мүдделер қақтығысы жоқ деп мәлімдейді.

БЛАГОДАРНОСТИ / ИСТОЧНИК ФИНАНСИРОВАНИЯ

Исследование проводилось с использованием частных источников финансирования.

КОНФЛИКТ ИНТЕРЕСОВ

Авторы заявляют, что конфликта интересов нет.

1 INTRODUCTION

In the context of active housing and infrastructure construction in the Republic of Kazakhstan, there is a steady growth in demand for ceramic building products. Such products are in demand due to their high strength, durability, thermal resistance, and compliance with modern energy efficiency requirements.

The development of building ceramics in the Republic of Kazakhstan holds one of the key positions in the state policy in the field of industrial and housing development. This direction is reflected, in particular, in the national project «Strong Region – Driver of Country's Development» for 2021-2025, the main goal of which is to improve the quality and affordability of housing.

Additionally, within the framework of implementing the Concept for the transition to a «Green» economy, emphasis has been placed on expanding the use of environmentally friendly and energy-efficient materials, including ceramic products. The regulatory framework also supports these goals: current building codes and technical regulations contain requirements aimed at ensuring the quality, safety, and environmental sustainability of construction products on the domestic market.

Despite the presence of significant reserves of natural clays, certain regions of Kazakhstan are experiencing a shortage of high-quality clay raw materials, which affects the sustainability and volume of ceramic product manufacturing. According to the Ministry of Industry and Construction of the Republic of Kazakhstan, in 2021, domestic enterprises provided only 44% of the internal demand for ceramic bricks, highlighting the need to seek alternative raw material solutions.

One of the potential solutions may be the use of ash and slag waste (ASW) from thermal power plants (TPPs), which allows for the simultaneous resolution of resource conservation and environmental safety issues. According to statistics, approximately 1.9 million tons of ash and slag are processed annually in Kazakhstan, accounting for less than 8% of the total amount generated. The Committee for Environmental Regulation and Control of the Ministry of Ecology and Natural Resources of the Republic of Kazakhstan estimates that over 17 million tons of ash are sent to ash dumps each year. Projections indicate that without large-scale utilization, the total volume of accumulated ash and slag could reach 1 billion tons by 2030.

Against this backdrop, the scientific and practical importance of developing technologies for processing ash and slag as a component of forming masses for construction ceramics is increasing. Among the fundamental works dedicated to this area, it is worth noting the monograph by S. Zh. Saibulatov, S. T. Suleimenov, and A. V. Ralko titled «Ash-Ceramic Wall Materials» **(Saibulatov et.al., 1982)**, which provides a detailed examination of the mechanisms of mineral formation, phase transformations, and strength characteristics of products based on ash and clay.

2 LITERATURE REVIEW

A number of works by Russian and Kazakh researchers confirm the applicability of ash and slag waste (ASW) as a plasticizing and fluxing additive that improves the technological properties of ceramic masses **(Nemushchenko et.al., 2024; Malchik et. al., 2016; Vatin et.al., 2016).**

Using the example of ash and slag from the Tolyiatti Thermal Power Plant, their ability to correct the plasticity and thermal resistance of ceramic mixtures was established **(Safronov et.al., 2021)**. Other studies **(Abdrakhimov, 2019; Gostev & Karagulov, 2020; Abdullaeva & Takibaeva., 2024; Aleksandrova & Korchevenkov, 2017)** demonstrated the possibility of producing solid M150 bricks with the addition of up to 25% ASW, as well as a reduction in energy costs for drying and firing processes.

Industrial examples have also been implemented in Kazakhstan: at Pavlodar brick factory No. 3, the addition of 12-15% ash and slag from TPP-1 helped eliminate shrinkage and cracking of the clay mass, increase strength, and improve the geometry of products **(Lazareva & Kulikova, 2016)**. Ash and slag from the Ekibastuz GRES-1, containing up to 25.7% Al_2O_3 and SiO_2 were successfully used, demonstrating strength up to 17 MPa when fired at 1000-1050º C **(Akhmedyanov et.al., 2015)**.

In addition, the formulations developed in the Pavlodar region with the participation of ASW confirm the industrial applicability of this approach **(Aryngazin et.al., 2022; Shaimerdenov & Shukurov, 2024; Vyshar et.al., 2023; Aldungarova et.al., 2021)**.

Additional research once again confirms the expediency of using ash and slag waste from thermal power plants in the production of ceramics. A comprehensive assessment of the ASW composition revealed the presence of reactive aluminosilicate microspheres, which improved water retention capacity and enhanced the physical-mechanical properties of mineral-based materials **(Kosivtsov et al., 2021)**. A modern approach to incorporating ash and slag waste into ceramic technology was demonstrated in a study focusing on three-component mixtures composed of aluminosilicate loams, ASW from thermal power plants, and fluxing additives such as cullet and silica gel. These additives enhanced mineral formation during firing, reduced the required heat treatment temperature, and increasing mechanical strength compared to binary compositions (loam + ASW) **(Gur'eva & Doroshin, 2024).**

3 MATERIALS AND METHODS

X-ray fluorescence (XRF) analysis was conducted using a Bruker spectrometer S2 Puma, and identification and quantification of crystalline phases using X-ray diffraction (XRD) on a Bruker diffractometer D6 PHASER. Both instruments are calibrated according to the manufacturer's standards and certified references, ensuring metrological traceability and high data reproducibility.

In the case of XRF, the pressed tablet or fused bead method was used, depending on the nature of the sample. For finely dispersed samples, pressing with an inert binder under a pressure of 20 t/cm² was applied (ASTM C114-23, ASTM E1621-13). Calibration was performed using CRM/ERM standards with expected concentration ranges. Spectrum recording was performed at 50 kV – 50 mA (Rh tube), collimator – 0.5 mm; calculation – by fundamental regression with peak overlap correction and verification using internal control samples (RSD < 2 %).

Samples for XRD were ground to < 63 µm in a planetary mill, ensuring random packing. Bragg-Brentano geometry was used with Cu Kα tube (λ =1.5406 Å), 40 kV – 40 Ma, slit – 0.6 mm, graphite monochromator. Scanning parameters: 5º – 70º 2θ, step 0.02, 1 s/step. Qualitative phase analysis was carried out according to the ICDD database PDF 4+ (2025).

Quality control included repeated measurements every 10 samples, laboratory blanks, and daily adjustments. This allowed keeping RSD below 0.5% for major elements (XRF) and < 1 % for peak intensities (XRD).

Figure 1 shows the ash and slag waste used at the Pavlodar TPP-3 and clay from the Pavlodar deposit.

Figure 1 – The studied ash and slag waste and clay [author's material].

4 RESULTS AND DISCUSSION

This study aims to assess the suitability of ash and slag waste from the Pavlodar region thermal power plant for the production of building ceramics. The efficiency of ash and slag use is determined by their compliance with the physical and chemical requirements for clay raw materials: dispersion, phase composition, oxide, and impurity content.

Ash and slag from thermal power plants are a finely dispersed gray material consisting of microspheres and angular particles. According to the data of the reclamation project for the ash dump of thermal power plant 2, up to 88% of the particles are 0.25-0.01 mm in size, which provides favourable conditions for the formation of a dense ceramic structure.

The composition of Ekibastuz ash and slag is represented by aluminosilicates, including mullite, quartz, hematite, and magnetite. Chemically, the oxides SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, and TiO_2 predominate.

The established characteristics confirm the potential applicability of ash and slag from TPP-3 as a functional component in the composition of clay raw materials for building ceramics.

X-ray fluorescence (XRF) analysis allowed determining the mass fraction of the main oxides in the studied samples: ash and slag from Pavlodar TPP-3 (Sample 1) and natural clay from the Pavlodar deposit (Sample 2).

Ash and slag are dominated by SiO_2 (61.19%) and Al_2O_3 (18.61%), which determines their aluminosilicate nature. A significant content of Fe_2O_3 (14.49%), as well as fluxing oxides K_2O, CaO, MgO, in total exceeds 10%, which makes it an effective component for lowering the sintering temperature.

The clay is characterized by a higher content of Al_2O_3 (28.39%) and Fe_2O_3 (26.88%), with a comparatively moderate proportion of SiO_2 (51.08%), which contributes to its tendency for intense coloration and the formation of a dense ceramic body at firing temperatures of 1100–1200 ºC. The comparative oxide composition of ash and clay is presented in **Table 1**.

Table 1
Comparative oxide composition of the studied samples [author's material]

Name of the raw material component	Oxide composition, mass %								
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	TiO_2	K_2O	SO_3
Clay	51.08	28.39	14.32	2.9	0.9	0.02	1.32	0.48	0.19

ASW of TPP-3	6 1.19	18.61	7.64	3.86	3.46	0.09	0.95	3.36	0.4

The chemical characteristics of the ash-slag waste allow it to be considered both as a fluxing and structural additive. The high content of fluxing components (K_2O, CaO, MgO) ensures a reduction in the initial sintering temperature, while Al_2O_3 and SiO_2 provide structural stability under thermal exposure. The presence of Fe_2O_3 contributes to the formation of an intense coloration.

The clay belongs to high-alumina, red-firing masses. The high concentration of Al_2O_3 ensures thermal resistance and shape stability during firing. The increased Fe_2O_3 content determines the characteristic dark-red coloration of the products. The combined data indicate the feasibility of blending ash-slag waste with clay to optimize the recipe of the ceramic mass.

X-ray phase analysis, performed in the 2θ range from 5º to 70º, made it possible to determine the mineral composition of the studied samples – ash and slag as shown in **Figure 2** and clay as shown in **Figure 3.**

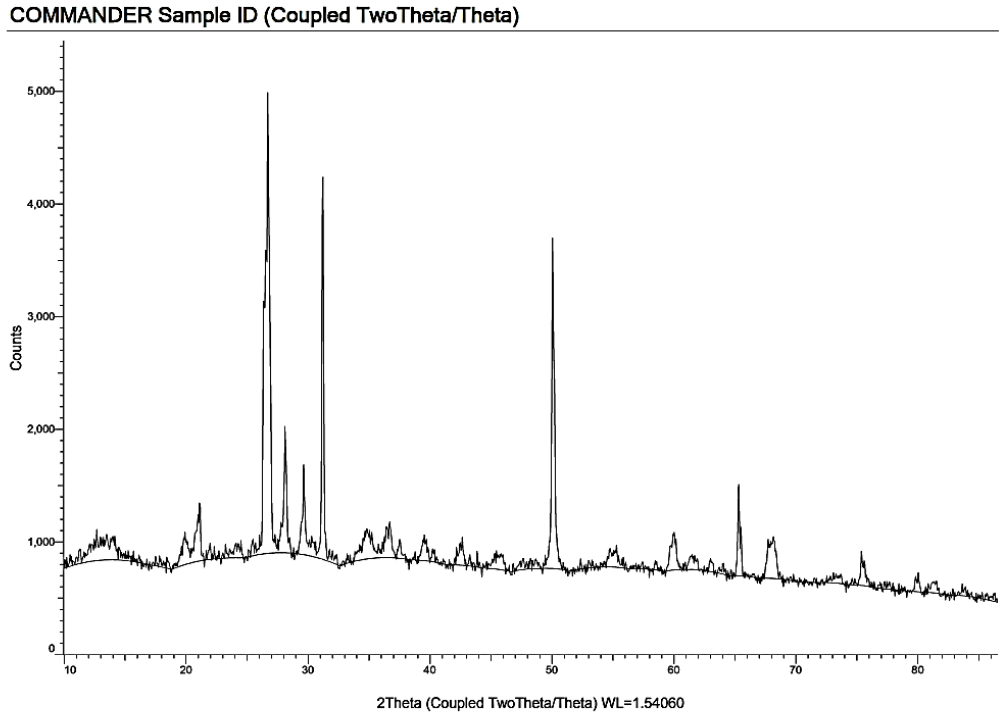

Figure 2 – Diffractogram of ash and slag from TPP-3 in Pavlodar region [author's material].

The ash-slag sample is characterized by an intense peak around 26.6º 2θ, which corresponds to the main reflection of quartz (SiO_2). Additionally, reflections corresponding to mullite ($Al_6Si_2O_{13}$) and anorthite ($CaAl_2Si_2O_8$) were identified. The presence of a broad background in the range of 15–35º indicates the existence of an amorphous glassy phase. Secondary peaks may be associated with hematite (Fe_2O_3) and rutile (TiO_2), which supports the chemical analysis data regarding Fe and Ti content.

The clay sample contains phase components typical of clay raw materials: kaolinite (peaks at ~12.3º, ~24.9º, ~38.5º), illite/muscovite (peaks at ~8–10º, ~17–20º, ~26º), as well as feldspars (orthoclase, microcline, albite) in the 28–31º 2θ range. The presence of hematite is confirmed by peaks in the 33–35º and ~54º ranges. An intense quartz peak (~26.6º) also dominates, indicating a significant content. The amorphous component, expressed by a broad background, is characteristic of fine-grained phases and poorly ordered silicates.

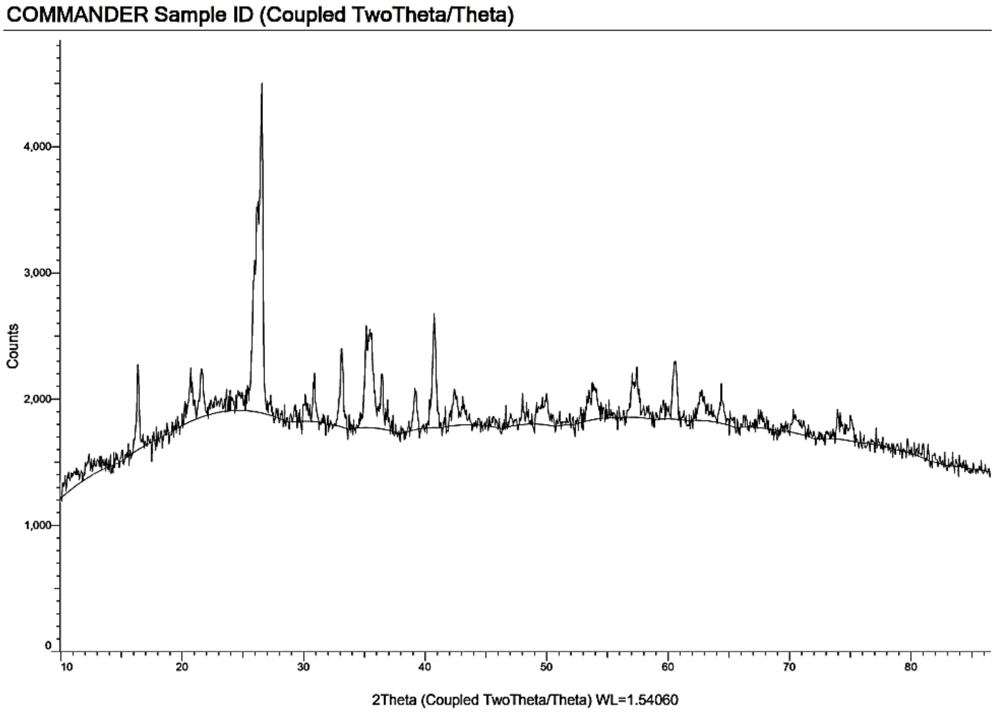

Figure 3 – Diffractogram of clay from the Pavlodar deposit

5 CONCLUSIONS

Based on the research results, the following conclusions can be drawn:

1. The chemical and phase analyses have confirmed that ASW from thermal power plants can be effectively used as a functional additive to clay raw materials for the production of building ceramics.
2. The presence of fluxing oxides (K_2O, CaO, MgO) and amorphous glassy phases in the ASW facilitates low-temperature sintering, while aluminosilicates (SiO_2, Al_2O_3) provide structural integrity and thermal resistance of the ceramic body.
3. The studied ash and slag from the Pavlodar TPP-3 are compatible with the high-alumina red-firing clays from the Pavlodar deposit, supporting the formation of dense, thermally stable ceramic materials.
4. The use of ASW in ceramic formulations reduces energy consumption during firing and contributes to cost saving in ceramic production.
5. Incorporating ASW into building ceramics promotes environmental sustainability by reducing the volume of industrial waste and mitigating its environmental impact, while simultaneously expanding the raw material base.

Further research should be aimed at optimizing the composition of ceramic products by selecting an effective ratios of ash and slag waste.

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