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Innovative approaches to the processing of ash and slag materials from the fuel and energy sector in the context of sustainable development

S.M. Nurmakova[1], U.K. Sarsembin[1], A. Dalbanbay[1], G.K. Abilova[2], B.K. Tusupova[3*], L.S. Kurbanova[3], G.B. Zharkimbaeva[1], M. Shanbayev[4]

[1]*Satbayev University, Almaty, Kazakhstan*

[2]*K. Zhubanov Aktobe regional university, Aktobe, Kazakhstan*

[3]*Al-Farabi Kazakh National University, Almaty, Kazakhstan*

[4]*G. Daukeev Almaty University of Power Engineering and Telecommunications, Almaty, Kazakhstan*

**Corresponding author: tussupova@yandex.ru*

Abstract. The whole world aims to reduce coal consumption, but despite such a policy, there are countries where its consumption continues to grow (China, India). If coal consumption grows, the volume of ash and slag waste (materials) that must be utilized and processed to obtain final products grows. The main elements included in the by-product of coal combustion are SiO_2, Al_2O_3, and Fe_2O_3. The paper provides a review of the use and processing of ash and slag materials for recycling as well as potential directions for their disposal: as well as potential directions for their disposal: cement production, geopolymer, in zeolite synthesis, microsphere separation, in agriculture, in land reclamation, in phytoremediation as reagents for water purification, in road construction for backfilling abandoned mines. The authors employed physicochemical analysis methods to confirm that the primary components of the material are SiO_2 (65.9%) and Al_2O_3 (22.5%). It has been established that a high proportion of silicon and aluminum can be an effective raw material for construction and geopolymer materials, as well as in the production of ceramic products. Availability of Fe_2O_3 (5.54%) suggests possibilities for its use in catalytic processes and pigment production. The alkaline reaction of the aqueous extract of the ash (pH = 9.25) correlates well with its chemical composition and confirms the presence of active alkaline components in the material. This alkaline nature of the ash favors geopolymerization processes and increases the material's reactivity when interacting with acidic activators. Additionally, the minor presence of TiO_2 (1.11%) may improve the mechanical properties of ash-based materials.

Keywords: *circular economy, green economy, industrial waste, ash and slag dumps, greenhouse gases, fly ash, ash and slag materials, fuel slag, ash and slag mixture.*

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1. Introduction

Kazakhstan has committed itself to the international community to accelerate the reduction of the share of natural hydrocarbons in the country's energy balance, namely, replacing coal as the least environmentally friendly energy source. And this fact plays a huge role in strengthening the climate agenda (SDG 13), thereby calling for abandoning hydrocarbon energy sources in the future and achieving carbon neutrality by 2060 [1], linking this with alternative energy. However, another side to this issue is the low reliability of these energy resources, which depend on unstable weather conditions in Kazakhstan. Another fact of «acceptance» of coal is the final agreement following the UN Climate Conference (COP 26), which recorded a deal to «gradually reduce» rather than «stop» coal consumption. The agreement also calls for intensifying efforts to reduce the volume of electricity production at coal-fired power plants. Still, it specifies that this only applies to those that do not have carbon dioxide capture technologies. By the Decree of the President of the Republic of Kazakhstan dated June 10, 2024, amendments were made to the transition to a green economy. The document stated that .... «The transition to a green economy is the main way to achieve the SDGs, fulfilling the promised contribution of Kazakhstan to reducing greenhouse gas emissions under the Paris Agreement while ensuring economic and environmental sustainability...». Coal energy remains a significant sector of industry, ensuring energy savings for most settlements and industrial sectors. However, the volume of accumulated slag materials reaches more than 30 million tons, and this problem is acute in the transition of the legislative and regulatory environmental framework to international standards. Another critical aspect of ecological sustainability for coal energy is the concept of a Circular Economy, aimed at eliminating the dependence of economic growth on the volume of natural resources and the transition from a linear economy to a circular one. This can be achieved by using existing funds and assets, materials and reserves, i.e., by reducing the volume of raw materials consumption and reducing the amount of waste generated [2].

Using coal as a primary fuel source results in a considerable amount of waste, depending on the method of capture and removal, such as slag, fly ash, and other by-products that must be disposed of and processed by the natural resource user. In a few countries, ash and slag materials (ASM) are a by-product of coal combustion, which, due to the wide variety of solid fuels, different combustion conditions, as well as different methods of capture and removal, differ in chemical and mineralogical composition, physical properties, melting point, radioactivity and other characteristics [3].

According to the legislation of Kazakhstan, namely Article 130 [4], ash and slag are classified as «technogenic mineral formations (TMF) of energy production in the production of electric and (or) thermal energy by generating units». According to the Waste Classifier, ash and slag are non-hazardous waste. That is, we can observe a contradiction in the regulatory framework of the Republic of Kazakhstan, where ash and slag are classified as both TMF and «waste». For successful management of ash and slag at the enterprises of the fuel and energy complex of the Republic of Kazakhstan, the first step should be a legislative change in the status of ash and slag and the use of the term «ash and slag materials» or «by-product of coal combustion», which can be used in various sectors of the economy of the Republic of Kazakhstan.

2. Materials and methods

During the combustion of solid fuel, and depending on the method of capture and removal, the following coal combustion by-products are formed:

1) fly ash – finely dispersed material (particle size from 3-5 to 100-150 µm), formed from the mineral part of pulverized fuel, captured by special devices from the flue gases of thermal power plants;

2) fuel slag – aggregated and fused ash particles from 0.15 to 40 mm in size;

3) ash and slag mixture – a mixture of fly ash and slag formed during their joint removal to the dump.

The formed coal combustion by-products (CCB) are shown in Figure 1, and their main types are shown in gaseous and solid states.

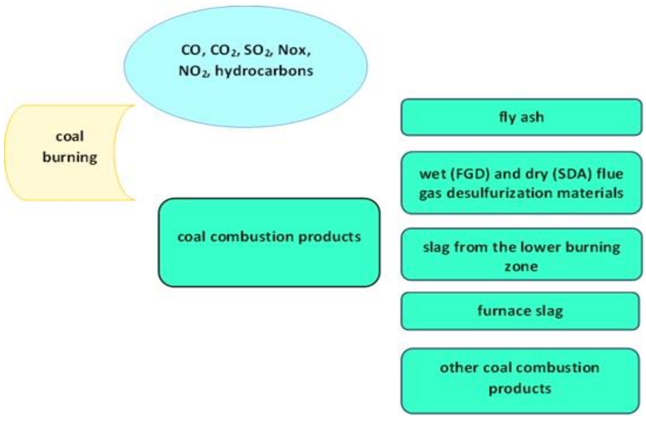

Figure 1. Classification of coal combustion products according to WWCCPN [5]

Solid CCBs include fly ash, slag from the lower combustion zone, fuel slag, fluidized bed (FB) ash, and flue gas desulphurization products formed by dry and wet methods [6]. Here are several key areas where ash and slag materials can effectively utilize.

2.1. Use of CCBs in the production of construction materials

ASM has found the most excellent application in construction in cement and concrete technologies. Using ash and slag reduces the cost of production of construction materials (cement, dry mortar, concrete, foam blocks, bricks, paving slabs). To reduce the environmental impact associated with cement production (concrete), the use of other additives to cement, in addition to Portland cement clinker, is currently increasing. Ash and slag can be used as additives. The primary process in cement and concrete production technology leads to significant CO_2 emissions during the decomposition of limestone into calcium oxide at high temperatures created during combustion. For each kg of cement produced, there is 0.5-0.9 kg of fly ash, which, according to the authors, is one of the best solutions for reducing the consumption of fossil mineral resources, because a large amount of ash and slag can be obtained at a low price. Instead of disposing of ash and slag at landfills, they can be used in cement production, which is effective from an environmental and economic point of view and meets sustainable development goals.

This paper [7] discusses the use of fly ash in cement production. Study [8] presents data on the application of fly ash in concrete and the effect of a specific percentage content on fresh and hardened concrete (mechanical properties and durability, microstructure of fly ash, impact of the type and size of fly ash particles). In addition to fly ash with a high SiO_2 content, granulated blast furnace slag (GBFS) can also be used as an additive to Portland cement clinker [9-15]. The use of GBFS began in 1865 in Germany, while fly ash dates back to the beginning of the 20th century [16, 17]. The world production of these industrial by-products is approximately 900-1000 million tons for fly ash and about 140-330 million tons for blast furnace slag [18]. Both discussed components, like Portland cement clinkers, are produced in a high-temperature process and are commonly used as central components in cement and/or as concrete components.

The utilization rate of granulated blast furnace slag in the composition of cement and concrete is more than 90%, while fly ash is around 30% [19]. The relatively low utilization of fly ash is due to its variable quality and different coal combustion methods, such as combining coal combustion with a dry flue gas desulphurization process in fluidized bed boilers, etc. Study [20] analyzes the main trends regarding fly ash and granulated slag use in cement, concrete and other binder composites. Attention is also given to the properties and potential applications of using fly ash in cement composites as a product of other coal combustion methods and ash obtained from the combustion of alternative fuels, mainly biomass.

Information about «green concrete» is mentioned in the article [21]. The authors developed a technology for processing fly ash and carbon dioxide into a new type of concrete. «Green» concrete was created from a semi-dry mixture of fly ash by pressing, and then it was cemented and hardened by a hydration reaction and accelerated carbonation. The authors studied the role of Na_2CO_3 activation by «accelerated carbonation» during chemical reactions and phase transformations, by changing the mechanical properties and microstructure of new concrete from waste. Accelerated carbonation (up to 4 hours) improved the mechanical strength and microstructural integrity of concrete from fly ash, which worked more effectively with the addition of Na_2CO_3. As a result of activation of the fly ash mixture with sodium carbonate, various hydration products were obtained due to increased alkalinity and dissociated $CO3^{2-}$ ions. Therefore, accelerated carbonation transformed the initial hydration products, contributing to natural hardening (carbonation)—microscopic crystalline phases formed by carbonation mixed with hydrated matrix phases. As a result, the carbonate products formed in situ acted as cementing agents. They contributed to creating a new cement-like and binding microstructure in concrete obtained from waste without using traditional cement. The work's experimental part confirmed this method's technical efficiency, demonstrating the potential for recycling significant volumes of solid waste from landfills. The process allows for producing new types of cement-free carbon-activated concrete, which opens prospects for more environmentally friendly, urban and infrastructural construction.

The production of geopolymers is another area of the construction industry. Anti-slip materials are formed due to the alkaline activation of inorganic compounds rich in Al_2O_3 and SiO_2. This process includes the formation of a three-dimensional structure of SiO_4 and AlO_4. Geopolymer is a modified binder for Portland cement concrete obtained from fly ash. It exhibits high heat and chemical resistance, making it an excellent choice for constructing rigid pavements at air bases [22].

In study [23], fly ash is used for the production of bricks, the content of which improves the compressive strength of the brick and improves its frost resistance

The use of CCBs in road construction is a well-known fact, which is regulated by regulatory documents:

– GOST 9128-97 Asphalt concrete mixtures for roads, airfields and asphalt concrete.

– GOST 23558-94 Crushed stone-gravel-sand mixtures and soils treated with inorganic road and airfield construction binders.

– GOST 30491-97 Organic and mineral mixtures and soils reinforced with organic binders for road and airfield construction.

– ODM 218.2.031-2013 Methodological recommendations for using fly ash and ash-slag mixtures from coal combustion at thermal power plants in road construction.

2.2. Use of CCBs as backfill material in mines

Voids formed during the underground extraction of mineral resources in depleted mines can lead to artificial disasters, such as flooding due to subterranean water breakthroughs or earthquakes caused by mine collapses. Depleted mine spaces are often filled with a mixture of cement, sand, and gravel; however, this method is expensive and does not always restore the required strength and structure of the rock mass. As an alternative solution, industrial waste mixtures known as backfilling material fill abandoned mine spaces [24]. This waste mass helps prevent ground subsidence, increases the stability of underground structures by managing rock pressure, and prevents deformation of the overlying strata up to the surface. It also eliminates ore liquefaction, optimizes waste disposal methods, and offers numerous other advantages [25-30]. Backfilling materials may include mine tailings and special binders prepared at the surface. Naturally, any neutral industrial waste can be used for this purpose (e.g., fly ash and slag materials, construction waste, etc.). The advantages of this technology include easier roof control during ore extraction and the utilization of industrial waste at mining sites.

Backfill materials can be divided into two main groups. The first is cementless backfill material, and the second is cement [31, 32]. When using backfill material without cement, the waste material is filled without adding any binder. When using cemented backfill, a specific binder, such as Portland cement, is added to the solid waste mixture [33].

One type of cemented backfilling material is paste backfill [33-35]. A significant number of studies in the field of waste management focus on various binders and alternative pozzolanic materials [33], one of which is paste backfill. This material has been widely adopted worldwide and is currently in high demand. The advantages of paste backfill lie in its technical and economic benefits and its ability to incorporate large volumes of industrial waste compared to other backfilling technologies used in mining. Globally, more than 100 mines utilize this backfilling method [36].

In the study [37], the authors demonstrated that there are research results on the development of paste backfill for mines using tailings, fly ash, and slag. The potential for applying paste backfill in underground mines worldwide, particularly in India, was highlighted. It was noted that many studies have been conducted on strength properties, structural changes, economic feasibility, and leaching behavior of backfilling materials. However, the question of how strength evolves remains open.

2.3. Use of CCBs in agriculture, land reclamation and phytoremediation

Flue Gas Desulfurization Gypsum is a gypsum obtained by cleaning the flue gases of thermal power plants from SO_2 and SO_3 using the lime method with $Ca(OH)_2$:

$$SO_2+Ca(OH)_2+½O_2 \rightarrow CaSO_4 \cdot 2H_2O.$$

The resulting $CaSO_4 \cdot 2H_2O$ (calcium sulfate dihydrate) is an analogue of natural gypsum widely used in agriculture as a fertilizer.

In the study [38], the authors compare FGD gypsum's and natural gypsum's chemical properties, showing that these substances exhibit similar behavior and effects on the studied crops. However, FGD gypsum, which has a finer particle size, possesses a higher degree of purity than natural gypsum.

There are three main uses of gypsum in agriculture, according to the US EPA. (2008) Agricultural uses for flue gas desulfurization (FGD) gypsum, EPA530-F-08-009 [39]:

1. Source of nutrients for plants;
2. To improve the physical and chemical properties of the soil;
3. To change the structure of the soil. This promotes the formation of large soil aggregates, thereby reducing soil erosion and leaching of nutrients. It also supports rapid water absorption, reducing surface runoff of sediments with pesticides and other pollutants, preventing them from entering water resources.

As an example of nutrient application, studies on the yield of alfalfa and soybeans can be cited [38], where yields increased following the application of FGD gypsum. FGD gypsum was also studied on alfalfa crops [40], revealing that yields improved on soils with an acidic subsoil layer without affecting the concentration of heavy metals. However, the fluoride concentration in the plant biomass was reduced, leading to a «significant decrease in health risks for animals feeding on these plants». It was noted that using gypsum in highly sandy soils may increase the leaching rate of magnesium (Mg) and potassium (K) through the soil profile, potentially resulting in deficiencies of these nutrients.

The study [41] demonstrated the benefits of applying FGD gypsum and humic acid to improve the physicochemical properties of soil and enhance canola crop productivity.

According to Buckley, M.E., & Wolkowski, R.P., soybean yields increased with gypsum application rates up to 1.2 tons per hectare, but exceeding this rate led to a decline in yields to levels observed in the control plots (without fertilizer application) [42].

In study [43], an evaluation was conducted based on two summer experiments on using FGD gypsum to effectively reclaim flood-prone lands with high salinity and improve herbaceous and woody plant growth on these lands. The rate and extent of reclamation were assessed, driven by the accelerated desalination process resulting from the exchange of calcium ions (Ca^{2+}) with sodium ions (Na^{+}).

However, an alternative perspective is presented in [44], which states that the content of essential nutrients such as nitrogen, phosphorus, potassium, sulfur, calcium, and magnesium is low in waste materials, making fly ash and slag «biologically sterile». The lack of plant-available organic substances, particularly the low content of humic acids in ash and slug waste, indicates that their use as a nutrient source for plants is limited. The use of ash and slag waste as a substitute for traditionally applied liming materials for periodic and maintenance liming of acidic soils is also restricted. Studies [45] show that applying ash and slag waste may improve soil structure and water-physical properties. However, its use as a soil conditioner should be evaluated case by case, due to the potential for exceeding provisional permissible concentrations of arsenic and cadmium, which are classified as Class I hazardous elements. Study [46] also explores fly ash as a soil additive, emphasizing its physical characteristics, including structure, water retention capacity, bulk density, and pH, making it a promising material for agricultural purposes. Despite its potential benefits for agricultural use, including addressing nutrient deficiencies and pest control, fly ash can also contain toxic heavy metals and radioactive elements. Therefore, the amount and method of fly ash application depend on factors such as soil type, crop variety, prevailing agroclimatic conditions, and the specific properties of the ash itself. Another critical aspect of such studies is monitoring both qualitative and quantitative soil parameters, plant growth, and the content and bioaccumulation of heavy metals in environmental components due to excessive fly ash application [45-47].

Another promising direction for using coal combustion by-products (CCB) is phytoremediation, which is used to restore degraded lands, such as ash disposal sites. This technology involves using local or native plant species (shrubs, trees, grasses, aquatic plants) and associated microorganisms, as well as chelating agents to enhance the uptake of metals from waste by plants [47, 48]. The review [49] proposes the reclamation of ash and slag disposal sites through vegetation, shrub plantings, and microbial inoculants. Microbial consortia play a crucial role in the physicochemical transformation of ash materials, while the application of organic substances promotes the establishment of plant cover. The morphological, physiological, and antioxidant responses of plants grown on ash disposal sites are examined in detail. The review identifies plant species demonstrating high biomass production, strong nitrogen-fixing capabilities, and soil microbial diversity development support. These studies focus on the challenge of restoring vast areas of ash dumps to foster ecosystem resilience and return degraded lands to productive use – an approach aligned with the principles of the circular economy.

3. Results and discussion

Ash and slag materials (ASM), according to the Subsoil Use Code of the Republic of Kazakhstan, are classified as man-made mineral formations – products of pyrotechnological processes occurring in the combustion chambers of thermal power plants (TPPs). Depending on the type of solid fuel and the physicochemical processes occurring in these boiler units, ash and slag formation can occur without melt formation, partial melting, or complete melting of the original components. The release of gaseous and vaporous substances, decarbonization, melting, crystallization, and silicate formation of the initial raw material accompany this. Thus, the choice of utilization methods for ASM depends on its composition, fuel characteristics, and physicochemical and mechanical properties. The research used ash and slag materials from TPP-2, which were removed as slurry and pumped through a pipeline system to a designated area («map») of the ash and slag disposal site.

X-ray phase analysis of fly ash from the thermal power plant (Figure 2) showed that its crystalline structure predominantly consists of the following mineral phases: mullite ($Al_{4.64}Si_{1.36}O_{9.68}$, 47.4%), quartz ($SiO_2$, 41.0%), magnetite ($Fe_{2.946}O_4$, 3.7%), maghemite ($Fe_2O_3$, 3.5%), calcite ($CaCO_3$, 2.9%), and titanium dioxide (TiO_2, 1.6%). The predominance of aluminosilicate minerals (mullite and quartz) is due to the high content of SiO_2 and Al_2O_3 in the original coal. At the same time, the presence of iron oxides (magnetite, hematite), calcium (calcite), and titanium reflects the composition of the ash-forming components of the fuel. The identified phase composition of fly ash determines its physicochemical properties and potential application areas, for example, as a raw material for producing geopolymers, ceramics and construction materials.

X-ray fluorescence (XRF) analysis revealed that the main components of fly ash are SiO_2 (65.9%) and Al_2O_3 (22.5%). The high proportion of silicon and aluminum suggests that ash may be an effective raw material for building geopolymer materials and some ceramic applications. The presence of Fe_2O_3 (5.54%) opens up possibilities for its use in catalytic processes and pigment production.

The presence of alkaline earth and alkali metal oxides - CaO (1.94%), MgO (0.572%), Na_2O (0.913%) and K_2O (0.559%) causes the alkaline reaction of the aqueous extract of ash (pH = 9.25). This pH value correlates well with the chemical composition and confirms the presence of active alkaline components in the material. The alkaline nature of ash favors geopolymerization processes and increases the material's reactivity when interacting with acidic activators.

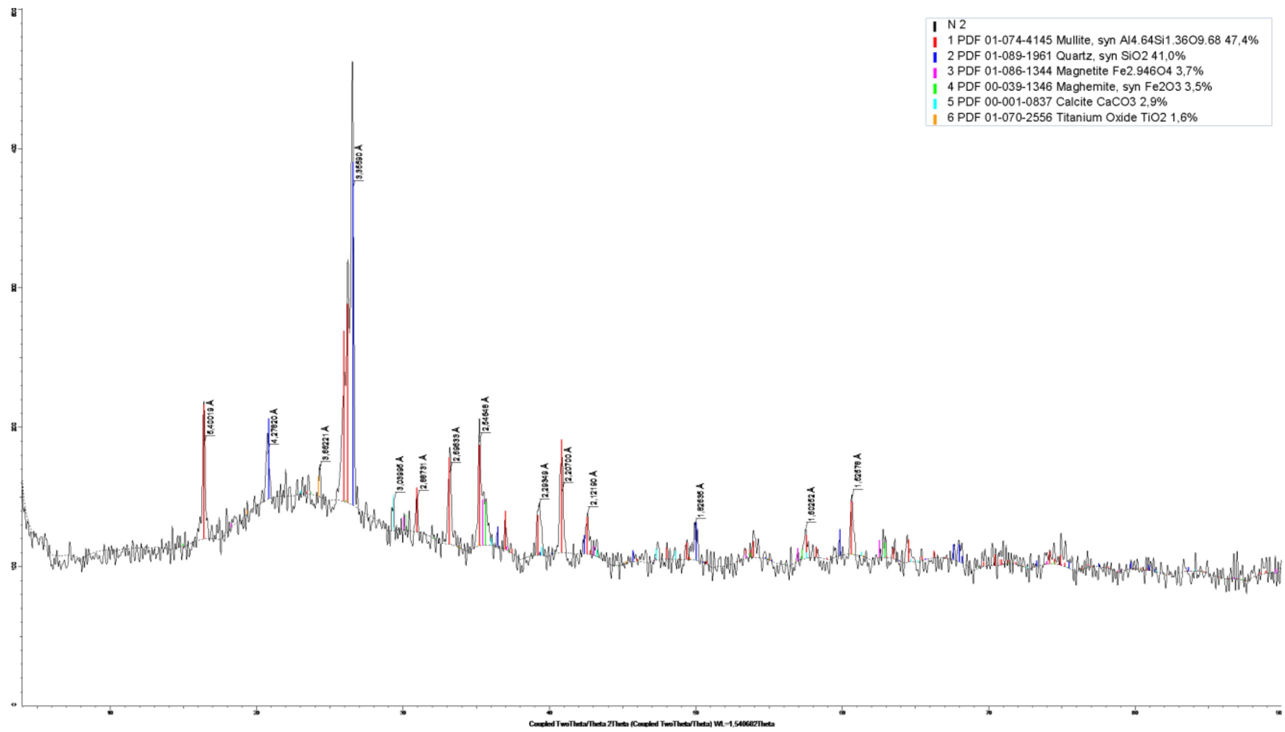

Figure 2. X-ray phase analysis of thermal power plant ash

TiO_2 (1.11%) can improve the mechanical properties of ash-based materials. The revealed ratio of the main components and the alkaline nature of the material determine the main areas of its practical application:

– as a precursor for the synthesis of geopolymers,

– as an active mineral additive in building mixtures,

– as a raw material for the production of ceramic materials,

– as a potential component of catalytic systems.

Ash and slag waste from the combustion of Ekibastuz coal at the Thermal Power Plant-2 in Almaty has the composition shown in Table 1.

Table 1. Results of X-ray fluorescence analysis of the main elemental composition of the initial samples of ash and slag waste at TPP-2 in Almaty

Sample name	Composition, %											
	K	Ca	Ti	Sr	Mn	Si	Fe	O	Zn	Al	Zr	C
Ash slag	0.185	1.72	1.06	0.017	0.17	23.91	8.75	49.9	0.006	11.3	0.016	1.75
Fine ash	0.166	1.14	1.12	0.016	0.067	24.3	2.58	50.47	0.03	12.45	0.017	6.64
Slag	0.174	1.49	1.43	0.031	0.08	26.02	4.54	52.2	0.02	12.89	0.02	0.19

As can be seen from the table, ash and slag contain the most silicon, aluminum, and iron. The bulk density of ash and slag is 1.07 g/cm^3; the sieve analysis results are presented in Table 2.

Table 2. Results of the sieve analysis of waste from Almaty TPP-2

Size, mm	Outlet, %
+1	0.044
0.5-1	0.044
0.2-0.5	7.08
0.1-0.2	35.1
0.071-0.1	23.7
-0.071	34.0
Total	100

The primary particle size class is -0.2+0 mm (92.83%). Considering the required size class (-0+0.74 mm), during the processing of technogenic raw materials, the proportion of material that involves grinding will not exceed 66.0%.

The study of aluminosilicate microspheres in ash and slag waste was carried out using a JEOL scanning electron microscope (Japan), equipped with an energy-dispersive X-ray analyzer «JCM-6000 PLUS» (Figures 3, 4).

Aluminosilicate microspheres are glass-crystalline aluminosilicate beads formed during high-temperature flame combustion of coal. They are the most valuable components of ash waste from thermal power plants. These are hollow, nearly perfectly shaped silicate spheres with smooth surfaces, ranging in diameter from 10 to several hundred micrometers, with an average of about 100 μm. This raw material is valuable for the production of construction materials. It can also be used as an inert material without additional processing.

Free aluminosilicate microspheres make up about 30% of the sample volume, while most of the sample consists of fragments of loose porous slags and, less frequently, individual crystals. In many cases, accumulations of the smallest microspheres are observed in the pores of the slag.

The size of aluminosilicate microspheres typically ranges from 1-3 micrometers (and fractions of a micrometer) up to 30-40 μm and rarely up to 100 μm. In addition to aluminosilicate microspheres, the sample also contains iron-rich microspheres (which appear light gray in the images). Alongside perfectly spherical formations, ellipsoidal, bulbous, globular shapes, «sphere-in-sphere» structures, fused aggregates of two or more spheres, and broken spheres and hemispheres.

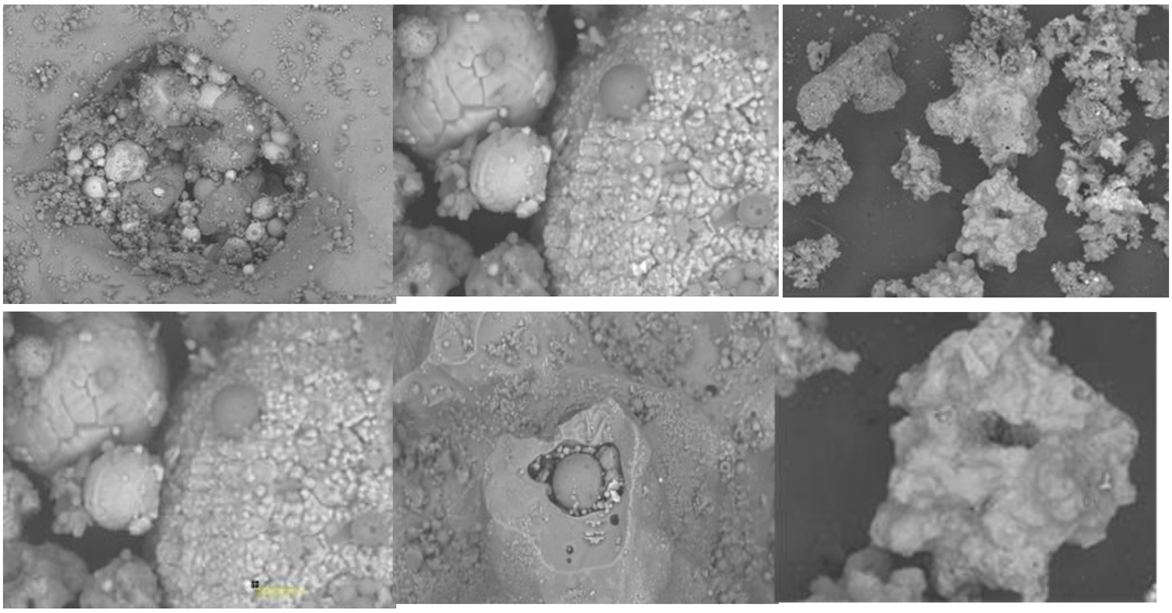

Figure 3. Slag particles

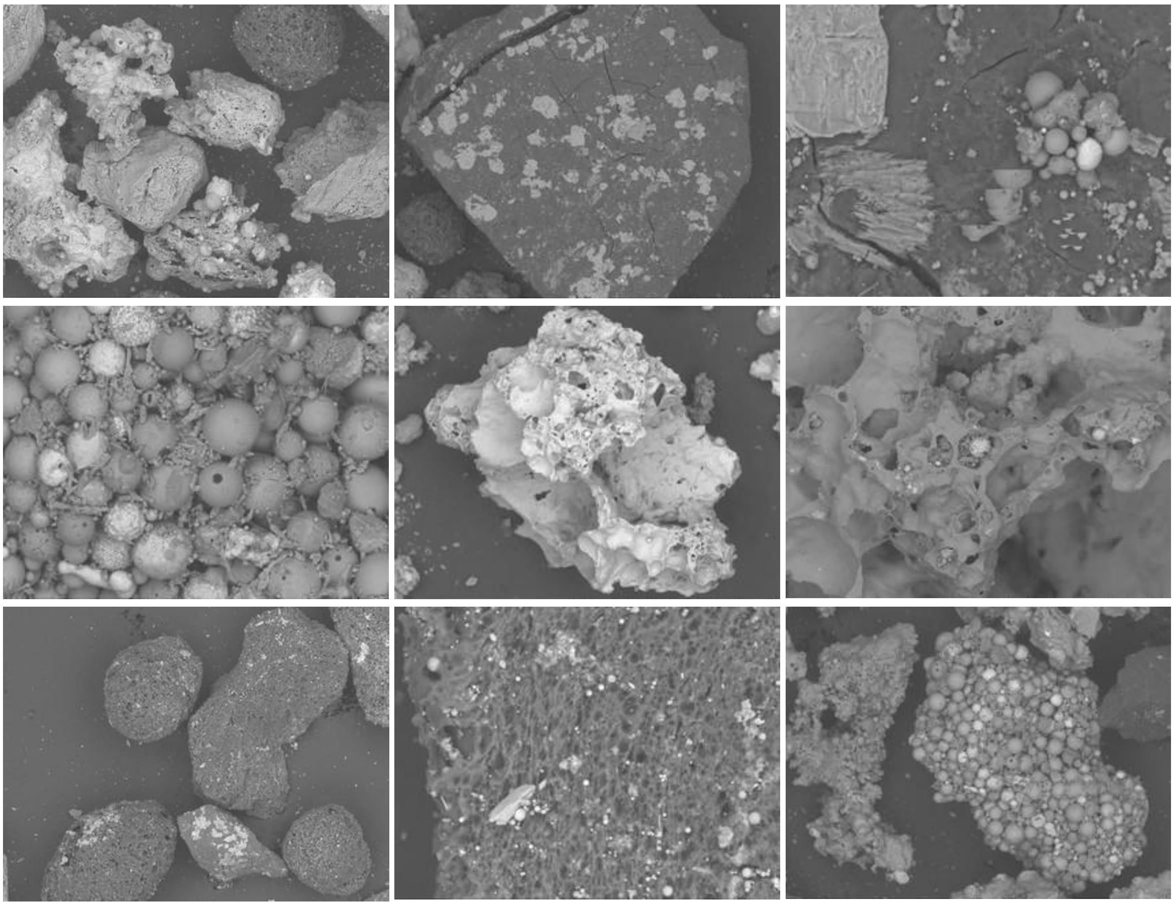

Figure 4. Different morphological types

The surface of aluminosilicate microspheres is generally smooth and dense, but it may also be porous, rough, or irregular (in cases of encrustations of different compositions or tiny microspheres). The surface of iron-rich microspheres is typically textured or ribbed due to the dense, patterned intergrowth of magnetite crystals; it may also be smooth when the microspheres are composed of iron with impurities or aluminosilicates with a high iron content. The composition of the aluminosilicate microspheres studied is somewhat variable. While the dominant elements remain Al, Si, and oxygen, the content of Mg, Ca, and Fe varies – for example, Ca may reach up to 17% by weight, and Mg up to 13% by weight. The composition also includes varying amounts of K, Na, Ti, S, P, and Cl. In some cases, the mineral composition of the microspheres is heterogeneous, showing tiny inclusions of carbonaceous material or fine disseminated intermetallic compounds such as Pb-Sn or Fe-Cr.

4. Conclusions

Analysis of scientific publications by foreign authors has led us to conclude that, first and foremost, ash and slag materials should be excluded from the «waste» category, as they represent a versatile material suitable for use in various industrial sectors. Moreover, valuable components extracted from them can be used to produce a wide range of products.

In addition, integrating coal combustion products from thermal power plants into industrial circulation will reduce their accumulation in ash disposal sites and prevent the storage of new volumes. This will contribute to the creation of zero-waste production systems and reduce the environmental burden of the fuel and energy sector. Research conducted at Satbayev University on ash and slag waste from TPP-2 in Almaty allows us to conclude that these materials can be used for the following purposes:

– as a precursor for the synthesis of geopolymers
– as an active mineral additive in building mixtures
– as a raw material for the production of ceramic materials.

Author contributions

Conceptualization: GKA, SMN, UKS; Data curation: BKT; Formal analysis: LSK, GBZ; Funding acquisition: GKA, UKS, SMN; Investigation: AD, SMN, UKS; Methodology: SMN, UKS; Project administration: GKA; Resources: AD; Software: GBZ; Supervision: SMN; Validation: AD; Visualization: GBZ, MS; Writing – original draft: SMN; Writing – review & editing: BKT, LSK. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

References

[1] On approval of the Strategy for achieving carbon neutrality of the Republic of Kazakhstan until 2060 (Decree No. 121). *Retrieved from:* https://adilet.zan.kz/rus/docs/U2300000121

[2] Concept for the transition of the Republic of Kazakhstan to a «green economy». *Retrieved from:* https://adilet.zan.kz/rus/docs/U1300000577

[3] Federal Road Agency. (2014). ODM 218.2.031-2013: Methodological recommendations for the use of fly ash and ash-slag mixtures from coal combustion at thermal power plants in road construction. Moscow

[4] Code of the Republic of Kazakhstan «On Subsoil and Subsoil Use» (No. 125-VI ZRK). *Retrieved from:* https://adilet.zan.kz/rus/docs/K1700000125

[5] Worldwide Coal Combustion Products Network. (n.d.). CCP basics. *Retrieved from:* http://wwccpn.org/ccp_basics.html

[6] World of Coal Ash. (2024). Craig Heidrich, Joachim Feuerborn. Global opportunities and challenges for coal combustion products with a circular economy. *Retrieved from:* https://worldofcoalash.org/wp-content/uploads/2022/09/global-opportunities-andchallenges-for-coal-combustion-products-with-a-circular-economy.pdf

[7] Kumar, N.D., Abhilash, P.P., Singh, R., Kumar, R., & Kumar, V. (2022). Fly ash for sustainable construction: A review of fly ash concrete and its beneficial use case studies. *Cleaner Materials*, (6), 100143. https://doi.org/10.1016/j.clema.2022.100143

[8] Zhang, Y., Smith, J., & Brown, L. (2022). Sustainable applications of coal combustion products in a circular economy. Environmental. *Advances*, (10), 100103.

[9] Siddique, R., & Cachim, P. (2018). Waste and Supplementary Cementitious Materials in Concrete: Characterisation, Properties and Application. *A volume in Woodhead Publishing Series in Civil and Structural Engineering*. https://doi.org/10.1016/C2016-0-04037-8

[10] Nguyen, H.A., Chang, T.P., Shih, J.Y., Chen, C.T., & Nguyen, T.D. (2015). Influence of circulating fluidized bed combustion (CFBC) fly ash on properties of modified high volume low calcium fly ash (HVFA) cement paste. *Construction and Building Materials*, (91), 208-215. https://doi.org/10.1016/j.conbuildmat.2015.05.075

[11] Giergiczny, Z., & Król, A.. (2008). Review Immobilization of heavy metals (Pb, Cu, Cr, Zn, Cd, Mn) in the mineral additions containing concrete composites. *Journal of Hazardous Materials*, *160*(2-3), 247-255. https://doi.org/10.1016/j.jhazmat.2008.03.007

[12] Fuller, A., Stegmaier, M., Schulz, N., Menke, M., Schellhorn, H., Knödler, F., Maier, J., & Scheffknecht, G. (2018). Use of wood dust fly ash from an industrial pulverized fuel facility for rendering. *Construction and Building Materials*, (189), 825-848. https://doi.org/10.1016/j.conbuildmat.2018.09.016

[13] Magdziarz, A., Dalai, A.K., & Koziński, J.A. (2016). Chemical composition, character and reactivity of renewable fuel ashes. *Fuel*, (176), 135-145. https://doi.org/10.1016/j.fuel.2016.02.069

[14] Martirena, F., & Monzó, J. (2018). Vegetable ashes as Supplementary Cementitious Materials. *Cement and Concrete Research*, (114), 57-64. https://doi.org/10.1016/j.cemconres.2017.08.015

[15] Nguyen, T.D., & Chang, T.P. (2015). Influence of circulating fluidized bed combustion (CFBC) fly ash on properties of modified high volume low calcium fly ash (HVFA) cement paste. *Construction and Building Materials*, (98), 448-455. https://doi.org/10.1016/j.conbuildmat.2015.05.075

[16] Nurpeisova, M., Estemesov, Z., Gabbasov, S., Ashimova, A., & Bek, A. (2023). Studying the properties of ash and slag waste for use in the manufacture of construction products. Mining of Mineral Deposits, 17(3), 102-109. https://doi.org/10.33271/mining17.03.102

[17] Rivera, F., Martínez, P., Castro, J., & López, M. (2015). Massive volume fly-ash concrete: A more sustainable material with fly ash replacing cement and aggregates. *Cement and Concrete Composites*, *63*, 104-112. https://doi.org/10.1016/j.cemconcomp.2015.08.001

[18] Marinković, S., & Dragaš, J. (2018). Fly ash. In K. M. A. Hossain & M. Lachemi (Eds.), Waste and Supplementary

Cementitious *Materials in Concrete, Elsevier*. https://doi.org/10.1016/B978-0-08-102156-9.00011-0
[19] Giergiczny, Z. (2019). Fly ash and slag. *Cement and Concrete Research*, (124), 105826. https://doi.org/10.1016/j.cemconres.2019.105826
[20] Liu, E., Kashwani, G., & Li, L. (2020). Transformation of industrial solid wastes into carbon-infused infrastructure materials. *Journal of Cleaner Production*, (260), 120890. https://doi.org/10.1016/j.jclepro.2020.120890
[21] Shill, S.K., Al-Deen, S., Ashraf, M., & Hutchison, W. (2020). Resistance of fly ash-based geopolymer mortar to both chemicals and high thermal cycles simultaneously. *Construction and Building Materials*, (239), 117886. https://doi.org/10.1016/j.conbuildmat.2019.117886
[22] Lingling, X., Wei, G., Tao, W., & Nanru, Y. (2005). Study on fired bricks with replacing clay by fly ash in high volume ratio. *Construction and Building Materials*, *19*(3), 243-247. https://doi.org/10.1016/j.conbuildmat.2004.05.017
[23] Panchal, S., Deb, D., & Sreenivas, T. (2018). Mill tailings based composites as paste backfill in mines of U-bearing dolomitic limestone ore. *Journal of Rock Mechanics and Geotechnical Engineering*, *10*(2), 310-322. https://doi.org/10.1016/j.jrmge.2017.08.004
[24] Senapati, P.K., Mishra, B.K., & Parida, A. (2013). Analysis of friction mechanism and homogeneity of suspended load for high concentration fly ash & bottom ash mixture slurry using rheological and pipeline experimental data. *Powder Technology*, *250*(3), 154-163. https://doi.org/10.1016/j.powtec.2013.10.014
[25] Behera, K., Ghosh, C.N., Mishra, D.P., Singh, P., Mishra, B.K., Buragohain, J., & Mandal, P.K. (2020). Strength development and microstructural investigation of lead-zinc mill tailings based paste backfill with fly ash as alternative binder. *Cement and Concrete Composites*, (109), 103553. https://doi.org/10.1016/j.cemconcomp.2020.103553
[26] Xu, W., Li, Q., & Liu, B. (2020). Coupled effect of curing temperature and age on compressive behavior, microstructure and ultrasonic properties of cemented tailings backfill. *Construction and Building Materials*, (237), 117738. https://doi.org/10.1016/j.conbuildmat.2019.117738
[27] Benzaazoua, M., Belem, T., & Bussière, B. (2002). Chemical factors that influence the performance of mine sulphidic paste backfill. *Cement and Concrete Research*, *32*(7), 1133-1144. https://doi.org/10.1016/S0008-8846(02)00752-4
[28] Ouellet, S., Bussière, B., Aubertin, M., & Benzaazoua, M. (2007). Microstructural evolution of cemented paste backfill: Mercury intrusion porosimetry test results. *Cement and Concrete Research*, *37*(12), 1654-1665. https://doi.org/10.1016/j.cemconres.2007.08.016
[29] Wu, D., Hou, Y., Deng, T., Chen, Y., & Zhao, X. (2017). Thermal, hydraulic and mechanical performances of cemented coal gangue-fly ash backfill. *International Journal of Mineral Processing*, (162), 12-18. https://doi.org/10.1016/j.minpro.2017.03.001
[30] Zheng, S., & Zhu, J. (2016). Utilization of limestone powder and water-reducing admixture in cemented paste backfill of coarse copper mine tailings. *Construction and Building Materials*, (126), 25-33. https://doi.org/10.1016/j.conbuildmat.2016.07.055
[31] Ghirian, A., & Fall, M. (2013). Coupled thermo-hydro-mechanical-chemical behaviour of cemented paste backfill in column experiments. *Part I: Physical, hydraulic and thermal processes and characteristics. Engineering Geology*, *164*, 195-207. https://doi.org/10.1016/j.enggeo.2013.01.015
[32] Koupouli, N.J.F., Belem, T., Rivard, P., & Effenguet, H. (2016). Direct shear tests on cemented paste backfill-rock wall and cemented paste backfill-backfill interfaces. *Journal of Rock Mechanics and Geotechnical Engineering*, *8*(4), 472-479. https://doi.org/10.1016/j.jrmge.2016.02.001
[33] Ercikdi, B., Baki, H., & İzki, M. (2013). Effect of desliming of sulphide-rich mill tailings on the long-term strength of cemented paste backfill. *Journal of Environmental Management*, (115), 5-13. https://doi.org/10.1016/j.jenvman.2012.11.014
[34] Zhang, L., Zhu, H., Zhou, B., & Zhang, M. (2014). Influence of fly ash and its mean particle size on certain engineering properties of cement composite mortars. *Powder Technology*, (253), 183-193. https://doi.org/10.1016/j.powtec.2013.10.014
[35] Behera, M., & Mishra, B. (2021). Utilization of mill tailings, fly ash, and slag as mine paste backfill material: Review and future perspective. *Construction and Building Materials*, (309), 125120. https://doi.org/10.1016/j.conbuildmat.2021.125120
[36] Chen, Z.W., Xiao, Y., Pang, L., Zeng, W.B., & Wu, S.P. (2014). Experimental assessment of flue gas desulfurization residues and basic oxygen furnace slag on fatigue and moisture resistance of HMA. *Fatigue and Fracture of Engineering Materials and Structures*, (37), 1242-1253. https://doi.org/10.1111/ffe.12205
[37] US Environmental Protection Agency (EPA). (2008). Agricultural uses for flue gas desulfurization (FGD) gypsum (EPA530-F-08-009). *U.S. Environmental Protection Agency*.
[38] Dhadse, S. (2024). Utilization of fly ash in agriculture: Perspectives and challenges. *Journal of Materials and Environmental Science*, *15*(7), 1038-1050.
[39] Nan, J., Chen, X., Wang, X., Lashari, M. S., Wang, Y., Guo, Z., & Du, Z. (2016). Effects of applying flue gas desulfurization gypsum and humic acid on soil physicochemical properties and rapeseed yield of a saline-sodic cropland in the eastern coastal area of China. *Journal of Soils and Sediments*, (16), 38-50. https://doi.org/10.1007/s11368-015-1186-3
[40] Buckley, M.E., & Wolkowski, R.P. (2012). Effect of land application of FGD gypsum on plant yield and crop nutrient concentration. *Crop Management.* https://doi.org/10.1094/CM2012-0925-01-RS
[41] Li, X., Mao, Y., & Liu, X. (2015). Flue gas desulfurization gypsum application for enhancing the desalination of reclaimed tidal lands. *Ecological Engineering*, *82*, 566-570. https://doi.org/10.1016/j.ecoleng.2015.04.010
[42] Chukaeva, M.A., Matveeva, V.A., & Sverchkov, I.P. (2022). Complex processing of high-carbon ash and slag waste. *Journal of Mining Institute*, 000, 1-8. https://doi.org/10.31897/PMI.2022.5
[43] Grebenshchikova, E.A., Yust, N.A., & Pykhteeva, M.A. (2016). The influence of chemical melioration by adding ash and slag waste on the physicochemical properties of the soil. *Bulletin of KrasSAU*, (6), 3-8.
[44] Dhadse, S. (2024). Utilization of Fly Ash in Agriculture: Perspectives and Challenges. *Journal of Materials and Environmental Science*, *15*(7), 1038-1050.
[45] Asante-Badu, B., Kgorutla, L.E., Li, S.S., Danso, P.O., Xue, Z., & Qiang, G. (2020). Phytoremediation of organic and inorganic compounds in natural and agricultural environments: A review. *Applied Ecology and Environmental Research*, *18*(5), 6875-6904. https://doi.org/10.15666/aeer/1805_68756904
[46] Banda, M., Matabane, L., & Munyengabe, A. (2024). A Phytoremediation Approach for the Restoration of Coal Fly Ash Polluted Sites: A Review. https://doi.org/10.20944/preprints202406.0768.v1
[47] Pandey, V.C., Abhilash, P.C., & Singh, N. (2009). The Indian perspective of utilizing fly ash in phytoremediation, phytomanagement and biomass production. *Journal of Environmental Management*, *90* (10), 2943-2958. https://doi.org/10.1016/j.jenvman.2009.05.001
[48] De Abreu, C.A., Coscione, A.R., Pires, A.M., & Paz-Ferreiro, J. (2012). Phytoremediation of a soil contaminated by heavy metals and boron using castor oil plants and organic matter amendments. *Journal of Geochemical Exploration*, (123), 3-7. https://doi.org/10.1016/j.gexplo.2012.04.013
[49] Yadav, S., Pandey, V.C., & Singh, L. (2021). Ecological restoration of fly-ash disposal areas Challenges and opportunities, 32(16). 4453-4471. https://doi.org/10.1002/ldr.4064

Тұрақты даму контекстінде отын-энергетика кешенінің күл-қож материалдарын қайта өңдеудің инновациялық тәсілдері

С.М. Нурмакова[1], У.К. Сарсембин[1], А. Далбанбай[1], Г.К. Абилова[2], Б.Х. Тусупова[3*], Л.С. Курбанова[3], Г.Б. Жаркимбаева[1], М. Шанбаев[4]

[1]*Satbayev University, Алматы, Қазақстан*
[2]*Қ. Жұбанов атындағы Ақтөбе өңірлік университеті, Ақтөбе, Қазақстан*
[3]*әл-Фараби атындағы Қазақ ұлттық университеті, Алматы, Қазақстан*
[4]*Ғ. Дәукеев атындағы Алматы энергетика және байланыс университеті, Алматы, Қазақстан*

**Корреспонденция үшін автор: tussupova@yandex.ru*

Аңдатпа. Бүкіл әлем көмір пайдалануды азайтуға бағытталған, бірақ мұндай саясатқа қарамастан, оны пайдалану көлемі өсіп жатқан елдер бар (Қытай, Үндістан). Егер көмірді пайдалану көлемі өссе, онда күл-қож қалдықтарының (материалдарының) көлемі артады, ал оларды кәдеге жарату немесе қайта өңдеу қажет. SiO_2, Al_2O_3, Fe_2O_3 көмірді жағудың жанама өнімінің құрамына кіретін негізгі элементтер. Жұмыста күл-қож материалдарын цемент, геополимер өндірісінде, цеолит синтезінде, микросфераны бөлуде, ауыл шаруашылығында, жерді мелиорациялауда, фиторемедиацияда, суды тазарту үшін реагент ретінде, жол құрылысында, пайдаланылған шахталарды толтыру кезінде пайдалану және қайта өңдеу, кәдеге жарату сияқты бағыттары бойынша шолу жасалған. Авторлар физикалық-химиялық талдау әдістерінің көмегімен күл қождарының негізгі құрамына SiO_2 (65.9%) және Al_2O_3 (22.5%) кіретінін растады. Нәтижесінде жоғары концентрациядағы кремний мен алюминий құрылыс және геополимерлік материалдар үшін, сондай-ақ керамикалық бұйымдар өндірісінде тиімді шикізат бола алатыны анықталды. Құрамындағы Fe_2O_3 (5.54%) каталитикалық процестерде және пигменттер өндірісінде қолдануға болады. Сулы күл сығындысының сілтілі реакциясы (pH = 9.25) күл қождарының химиялық құрамымен жақсы корреляциялайды және материалда белсенді сілтілі компоненттердің бар екендігін растайды. Осылайша, күлдің сілтілі табиғаты геополимерлеу процестеріне қолайлы болады және қышқыл активаторлармен әрекеттесу кезінде материалдың реакциялық қабілетін арттырады. Ал TiO_2-нің аз мөлшері (1.11%) күлге негізделіп жасалған материалдардың механикалық өнімділігін жақсартуға ықпал етуі мүмкін.

Негізгі сөздер: *циркулярлық экономика, жасыл экономика, өндірістік қалдықтар, күл-қож үйінділері, парниктік газдар, күлдің шығуы, күл-қож материалдары, отын қождары, күл-қож қоспасы.*

Инновационные подходы к переработке золошлаковых материалов топливно-энергетического комплекса в контексте устойчивого развития

С.М. Нурмакова[1], У.К. Сарсембин[1], А. Далбанбай[1], Г.К. Абилова[2], Б.Х. Тусупова[3*], Л.С. Курбанова[3], Г.Б. Жаркимбаева[1], М. Шанбаев[4]

[1]*Satbayev University, Алматы, Казахстан*
[2]*Актюбинский региональный университет им. К. Жубанова, Актобе, Казахстан*
[3]*Казахский национальный университет им. аль-Фараби, Алматы, Казахстан*
[4]*Алматинский университет энергетики и связи им. Г. Даукеева, Казахстан, Алматы, Казахстан*

**Автор для корреспонденции: tussupova@yandex.ru*

Аннотация. Весь мир нацелен на сокращение потребления угля, но несмотря на такую политику есть страны, где его потребление продолжает расти (Китай, Индия). Если растет потребление угля, то растет объем золошлаковых отходов (материалов), которые необходимо утилизировать, переработать с получение конечной продукции. В работе выполнен обзор по использованию и переработке золошлакоматериалов, и возможные направления утилизации: производство цемента, геополимера, в синтезе цеолитов, в разделении микросферы, в сельском хозяйстве, в мелиорации земель, в фиторемедиации, в качестве реагентов для очистки воды, в дорожном строительстве, при засыпке отработанных шахт. Физико-химическими методами анализа авторы подтвердили, что в основной состав золошлака входят SiO_2 (65.9%) и Al_2O_3 (22.5%). Вывод – кремний и алюминий, содержащиеся в высокой концентрации, могут быть эффективным сырьем для строительных и геополимерных материалов, а также в производстве керамических изделий. Наличие Fe_2O_3 (5.54%) открывает возможности для её использования в каталитических процессах и производстве пигментов. Щелочная реакция водной вытяжки золы (pH = 9.25) хорошо коррелирует с химическим составом золошлака и подтверждает наличие активных щелочных компонентов в материале. Тем самым щелочная природа золы благоприятствует процессам геополимеризации и повышает реакционную способность материала при взаимодействии с кислыми активаторами. А незначительное присутствие TiO_2 (1.11%) может способствовать улучшению механических характеристик материалов на основе золы.

Ключевые слова: *циркулярная экономика, зеленая экономика, производственные отходы, золошлакоотвалы, парниковые газы, золоунос, золошлакоматериалы, топливный шлак, золошлаковая смесь.*

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